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TESTING OF THE ENGINE COMPARTMENT FIRE EXTINGUISHING SYSTEM IN THE F/EF-111 AIRCRAFT

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Tests were conducted at the FAA Air Blast Test Facility during which Halon 1202 or Halon 1301 was discharged into the nacelle of an F/EF-111 test article through the aircraft's on-board agent distribution system. Various ground/flight conditions were simulated by providing controlled nacelle ventilating flows using by-pass air from a YTF-33 engine. Preliminary test indicated that some advantage resulted using the more volatile Halon 1301 agent. Tests also revealed that using either agent, the current on-board nacelle fire extinguishing system does not meet the recommended minimum requirements for an acceptable system in a major portion of the aircrafts operational flight envelope. And finally, the test results indicate that a revision to Mil-E-22285 should be considered. Keywords: Fire extinguishing agents, fire protection.

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FOREWORD

This final report was prepared by the Federal Aviation Administration (FAA) Technical Center, Atlantic City International Airport, New Jersey. This effort was sponsored by the Air Force Wright Aeronautical Laboratories, Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio at the request of McClellan Air Force Base, Sacramento, California. The work was accomplished under Contract Number MIPR FY 1455-87-N0606 for the period July 1986 to February 1987, Project 3048, Task 07 with Lt. M. Rodriguez as Program Monitor. Other FAA/Technical Center personnel were: G. Chamberlain, Program Manager; P. Boris, Project Manager; and Aerospace Engineering Technicians, A. Spezio, and J. Rosen.

The authors wish to thank the following persons for their assistance in conducting this project effort: Messers A. Johnson, R. Esch, and A. Meyer of the Boeing Company for their assistance in acquiring agent concentration data; Mr. T. Beutner of General Dynamics for his assistance in installing the EF-111 oil cooler; Mr. R. Springer of General Dynamics for providing nacelle ventilation data; Mr. B. Nichols of McClellan AFB for his assistance in providing oil cooler information; and Mr. R. Glazer of the Walter Kidde Company for providing Halon 1301 agent containers and hardware.

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EXECUTIVE SUMMARY

This effort was conducted in response to a request from McClellan AFB for assistance in determining the adequacy of the onboard Halon 1202 EF-111 Nacelle fire extinguishing system. Based upon questions raised concerning the limited scope of the original F-111 extinguishing system qualification testing, the project was subsequently expanded to include the entire ground and flight operating envelopes of both the F and EF-111 aircraft. Then, as a direct result of the Halon 1202 system testing, the project was further expanded to provide a preliminary investigation into the use of Halon 1301 as an alternate extinquishing agent for the existing distribution system. No distribution system modifications were attempted during the testing described herein. Each of the two distinct Halon test phases (1202 and 1301) are presented separately in this report (Part 1 and Part 2, respectively).

Tests were conducted at the Federal Aviation Administration (FAA) Technical Center's Air Blast Test Facility during which the Halon agent was discharged into the nacelle of an in-place, multi-use, F-111 test article under simulated ground and flight conditions. Extinguishing agent concentration was continuously and simultaneously measured at various locations throughout the nacelle.

Agent concentration and distribution are affected by nacelle ventilation rates. Using a recommended minimum criteria of 6 percent agent volumetric concentration persisting at all locations simultaneously throughout the nacelle for not less than 0.5 second, the test results indicated that the current system, charged with Halon 1202, is acceptable in the relatively low engine operating and ventilating flow ground condition with aircraft stationary. However, the test data further indicate that the aircraft's current extinguishing system does not provide the recommended minimum agent distribution requirements in a significant portion of the aircraft's operational flight envelope.

Using the same criteria for acceptance, the data indicated that the current F-111 nacelle fire extinguishing system, when charged with 10.9 lbs of Halon 1301, was satisfactory with nacelle ventilation rates produced in the cruise flight condition. Increasing the amounts of Halon 1301 discharged into the nacelle did provide criteria compliance at other flight conditions with higher ventilation rates. However, neither the standard charge of Halon 1202 (12.65 lbs) nor Halon 1301 up to a charge weight of 29.7 lbs resulted in an acceptable system at the sea level dash flight condition. The data indicate that the current F/EF-111 nacelle fire extinguishing system, whether charged with Halon 1202 or 1301, does not meet the recommended criteria over the entire operational flight envelope of the aircraft.

Finally, a significant conclusion was reached regarding the technical validity of MIL-E-22285, which deals with the acceptance testing of all military aircraft engine compartment fire extinguishing systems. It was concluded that a revision to this MIL SPEC should be considered to assure that acceptance testing is conducted under conditions that most adversely affect extinguishing system performance.

PART I-HALON 1202 AGENT CONCENTRATION TESTS

I INTRODUCTION

1.1 PURPOSE

The purpose of this test program was (1) to determine the ability of the current onboard EF-111 Halon 1202 engine bay extinguishing system to provide fire protection for the integrated drive generator (IDG) oil cooler, (2) to provide insight into the overall level of fire protection afforded the engine bay by the current F/EF-111 fire extinguishing system, and (3) to determine the effect of the IDG oil cooler installation on agent distribution.

1.2 BACKGROUND

Due to the increased electrical load of the EF-111 aircraft, it was necessary to provide additional oil cooling for the integrated drive generator. The placement of the oil cooler within the engine bay of the EF-111 aircraft increases the amount of flammables circulating in the fire zone. Failure of this system in the form of an oil leak could either contribute to the intensity of, or be the direct cause of, a nacelle fire. This oil cooling system is located entirely within the nacelle and, therefore, normal firewall shutoff is not integral to its design. The maximum operating temperature (325 degrees F), pressure (270 psi), and flow of oil (6.4 gpm), imply that the flammables would not necessarily be confined to the immediate area of the oil cooler. Indeed, depending upon the location and size of an oil leak, the flammables could be directed virtually anywhere in the nacelle. For this reason, it is not only necessary to provide fire protection for the oil cooler itself, but also to assure that the entire nacelle has adequate Halon 1202 fire protection.

1.3 TEST FACILITY

The tests described herein were conducted at the Air Blast Test Facility of the Federal Aviation Administration Technical Center, Atlantic City International Airport, New Jersey.

The Air Blast Test Facility is an outdoor test site which includes a YTF-33 air supply engine capable of providing air through a 30-inch-diameter duct at a variable rate up to a maximum of 200 lb/sec. The air is devoid of engine exhaust products, since it is collected from the forward fan of the YTF-33. The air is ducted to a 75 foot x 100 foot concrete test pad on which is secured an F-111 test article. The 30-inch duct gradually tapers to an 18-inch-diameter duct, the terminus of which is attached to the aircraft's splitter inlet, thus allowing ducted air to ventilate the engine bay. Excess air is dumped overboard upstream of the 30-inch to 18-inch transition section. The nacelle ventilation airflow to the test article is controlled by the YTF-33 throttle position and a remotely operated gate in the 30-inch-diameter duct. Figure 1 shows a schematic of the Air Blast Test Facility. Currently this facility does not have the fuel pumping capacity to maintain TF-30 operation in maximum afterburner (A/B). The TF-30 has five zones of afterburning, however, the maximum level of TF-30 operation for this test program was limited to zone 1.

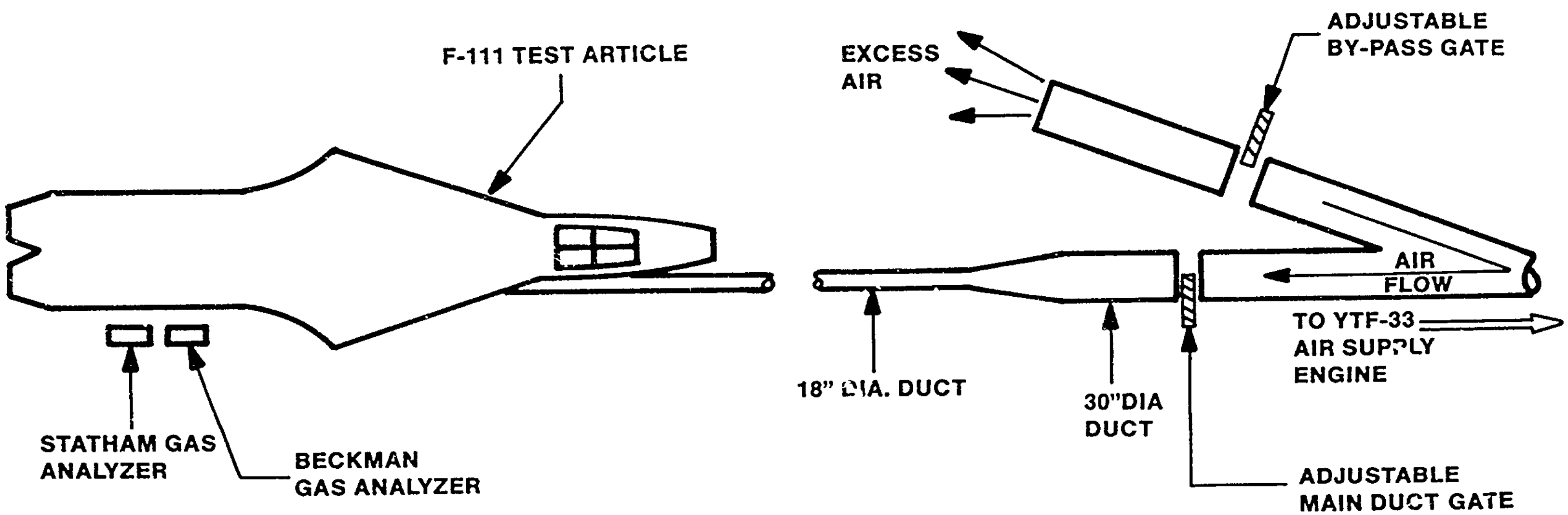


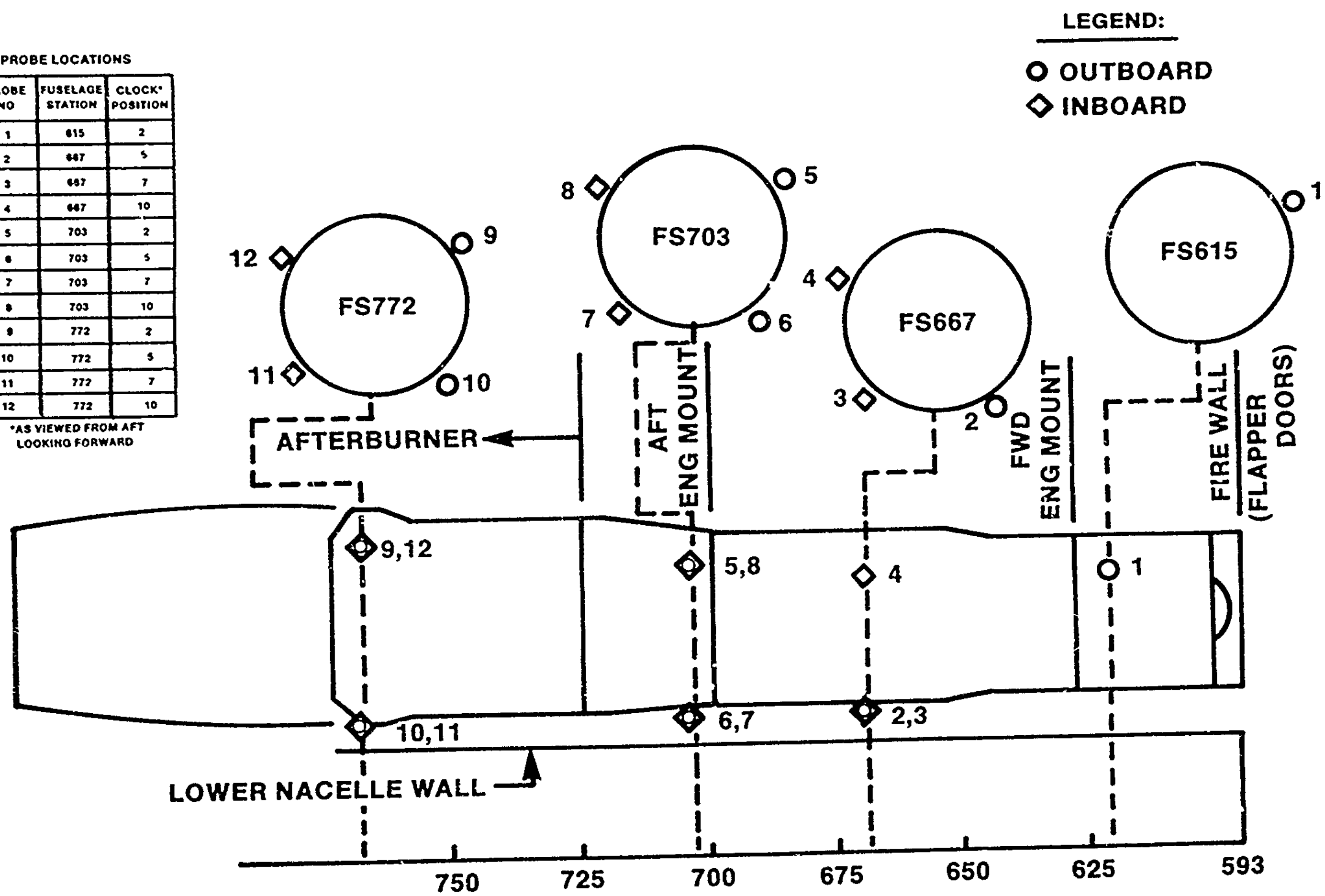
FIGURE 1. SCHEMATIC FOR AIR BLAST TEST FACILITY AND TEST INSTRUMENTATION

1.4 METHOD OF APPROACH

With the on-site assistance of General Dynamics, an IDG oil cooler and oil lines were positioned and installed in the F-111 test article. Difficulties were encountered while attempting to install the oil cooler as shown in Grumman Aerospace drawings. The required placement of the oil cooler resulted in interference with engine hardware and prevented the nacelle door from being fully closed and secured. It was mutually agreed upon by the FAA and McClellan AFB to find a suitable location closest to that specified on the drawing. For this test program, the oil cooler was installed in a position approximately 3 inches forward and 2-3/4 inches higher than its normal location. This resulted in the oil cooler attachment bracket overlapping the nacelle door hinge, however, this did not affect door closing. The oil cooler lines were attached to the oil cooler itself, but were not connected to the aircraft's oil circulation system. The unattached ends of the lines were secured to the TF-30 with safety wire at the locations where they would normally enter the aircraft's oil system.

Extinguishing agent sampling probes were installed at various locations throughout the nacelle. For general comparative purposes, the open ends of the probes were positioned in the same locations used by Walter Kidde Co. during the original fire extinguishing system acceptance test (General Dynamics Report No. FGT-5428, March 14, 1969). Direct comparison of the 1969 test and the current tests is difficult because of removal of the firewall flapper doors and changes in engine/accessory configuration in the intervening time period. The current tests were conducted with flapper doors removed. Eight tests were conducted with the sample probes in these locations and these tests were designated as the FOC-series. See figure 2 for FOC-series probe locations. Seven additional sampling probes were installed in alternate locations, two of which were in the immediate vicinity of the oil coooler. Three tests were conducted with the seven probes in these alternate locations, and these tests were designated as the OC-series. See figure 3 for OC-series probe locations. Note that four probes remained in the same location for both the FOC- and OC-series tests. Three final tests were conducted with the oil cooler removed and with the probe locations again as in the FOC-series tests. These tests were conducted to obtain data pertinent to the ground and in-flight performance of the current F-111A extinguishing system, and these tests were designated as the F-series.

Fourteen Halon 1202 tests were conducted, however only that test data which satisfies the statement of the purpose is included in the main body of PART I in this report. The remainder of the Halon 1202 data is presented and discussed in Section V of PART I. Each test was conducted in a similar manner: the TF-30 was started and allowed to stabilize at idle, the required nacelle ventilation rate was established with the YTF-33, the TF-30 throttle was positioned to obtain the required predetermined engine RPM, the recording instrumentation was turned on, the TF-30 throttle was chopped to idle, and the Halon 1202 container was discharged approximately 2 seconds after throttle chop. The throttle chop was performed to simulate normal fire emergency procedure. For all tests, the 385 in^3 agent containers were charged with a nominal 12.65 lbs of Halon 1202 and pressurized with nitrogen to 600 psig. Note that this quantity of agent in a 385 in^3 container is equivalent to about a 40 percent fill ratio, which is the standard Air Force fill ratio for the F/EF-111 aircraft. Using a normal 50 percent fill ratio, the 385 in^3 container could hold 15.9 pounds of Halon 1202.

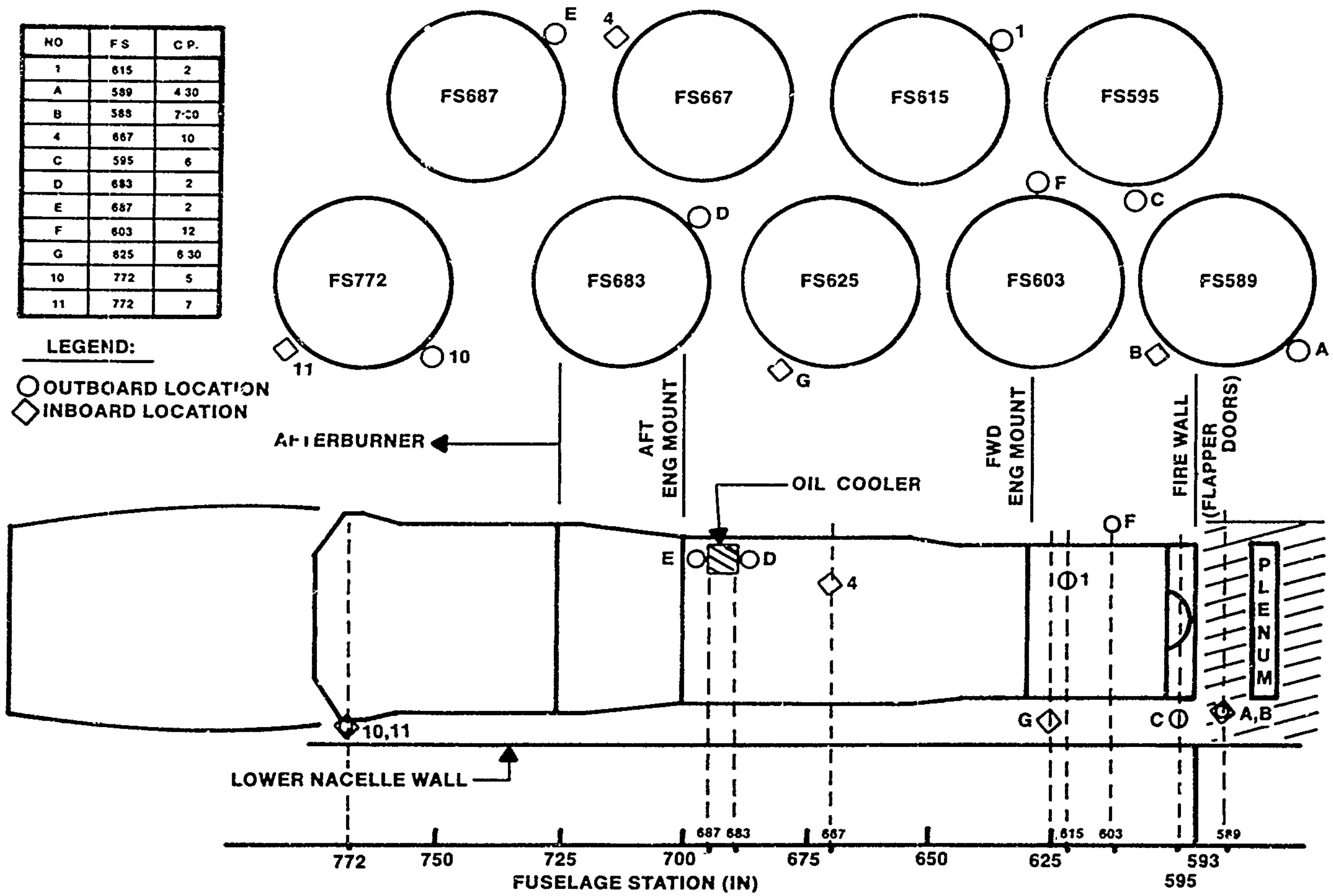


PROBE LOCATIONS

PROBE NO	FUSELAGE STATION	CLOCK* POSITION
1	615	2
2	667	5
3	667	7
4	667	10
5	703	2
6	703	5
7	703	7
8	703	10
9	772	2
10	772	5
11	772	7
12	772	10

*AS VIEWED FROM AFT LOOKING FORWARD

FIGURE 2. SAMPLE PROBE LOCATIONS FOR F AND FOC-SERIES TESTS



NO	F S	C P.
1	615	2
A	589	4 30
B	588	7 30
4	667	10
C	595	6
D	683	2
E	687	2
F	603	12
G	625	6 30
10	772	5
11	772	7

FIGURE 3. SAMPLE PROBE LOCATIONS FOR OC-SERIES TESTS

The criteria for acceptance or failure of the system for a particular flight or ground operating condition was based on MIL-E-22285, paragraph 3.8, Amendment-1, which states: "Actuation of the extinguishing system shall produce a concentration of agent at least 6 percent by volume in air in all parts of the affected zone. This concentration shall persist in each part of the zone for at least 0.5 second at normal cruising condition." This specification was only used as a guide, since the simulated test conditions included other than normal cruise. Additionally, MIL-E-22285 refers only to Halon 1301. The tests described herein utilized Halon 1202.

1.5 INSTRUMENTATION

The major instrumentation for this test program included:

- o Statham Gas Analyzer, Model GA-2A, 12 channel (7 operational)
- o Beckman Gas Analyzers, Model LB-2, 6 total
- o Honeywell Visicorders, Model 1858, 2 total
- o Accurex Ten/10 Data logger

A typical probe installation is shown in figure 4. Note that two sample probes are shown in this figure: the larger tube was used with the Statham Analyzer, and the smaller with the Beckman system. There was parallel installation of some probes to more readily accomplish switching between measurement systems in the event a channel of either system became inoperative. Throughout all tests, one of these parallel probe installations was monitored and recorded by both the Statham and Beckman analyzers/recording systems. In addition, the agent container squib firing signal was mutually recorded. These test parameters were simultaneously recorded to coordinate time and concentration data between the two analyzer systems. The accurex data logger was used to monitor mass airflow within the air supply duct leading into the F-111 test article. Figure 5 shows the schematic for agent concentration data collection.

II DISCUSSION

2.1 FOREWORD

The data presented in this report are considered sufficient and adequate to meet the purpose of this test program. In the main body of Part 1 are the figures showing the Halon 1202 agent concentration/distribution for tests nos. FOC-1, FOC-2, FOC-6 FOC-7, OC-1, OC-2, OC-3, and F-1, F-2, and F-3. These tests are representative of simulated aircraft operation from ar aircraft parked/engine operating condition through sea level dash. Additional pertinent Halon 1202 data, not specificallly related to the purpose, are presented and discussed separately in Section V.

2.2 TEST RESULTS

2.2.1 Test No. FOC-1 (Aircraft Parked/Engine Operating)

This test simulated the aircraft parked/engine operating ground condition for the EF-111 aircraft. Ventilation of the nacelle was accomplished solely by

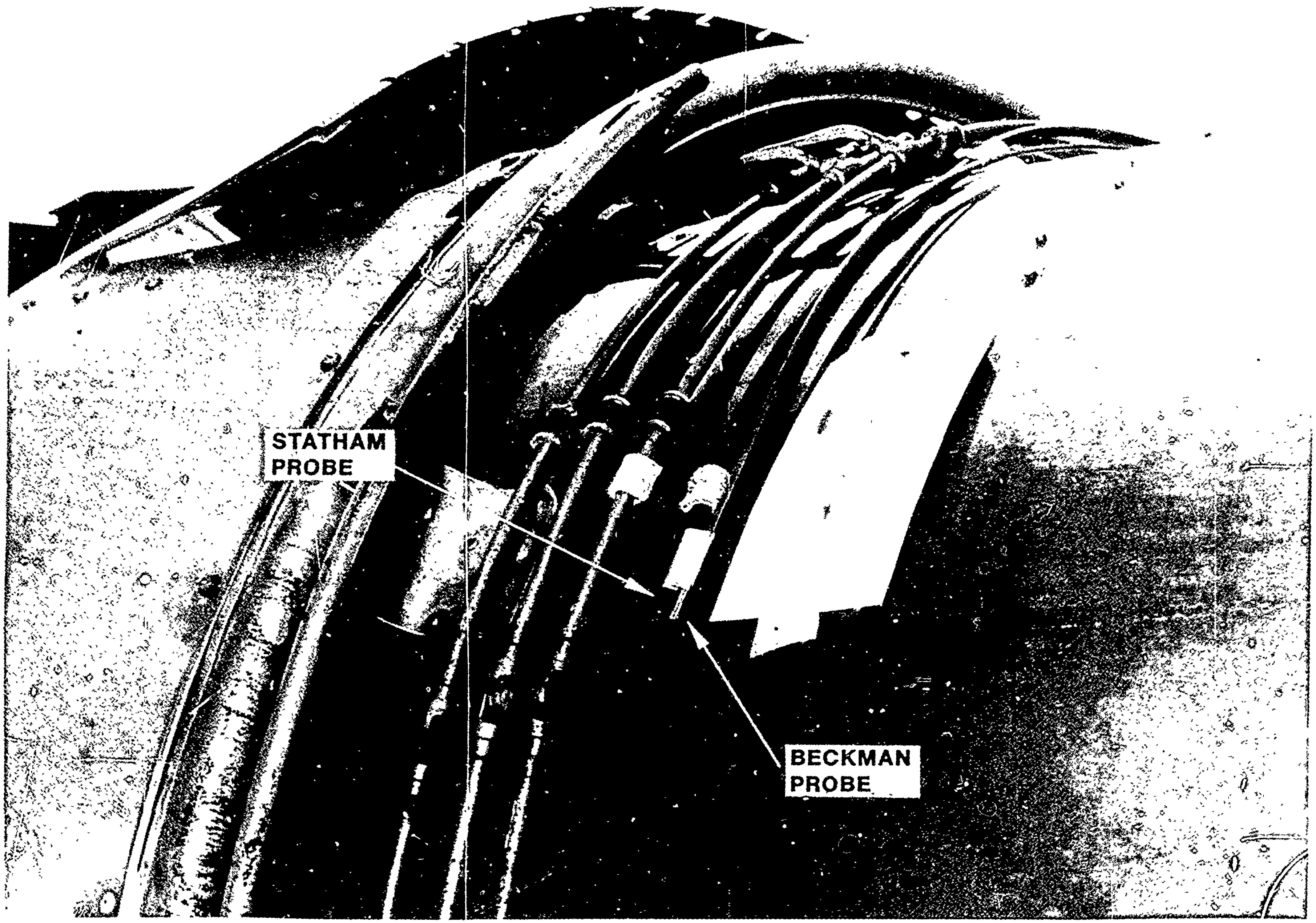


FIGURE 4. TYPICAL SAMPLE PROBE INSTALLATION

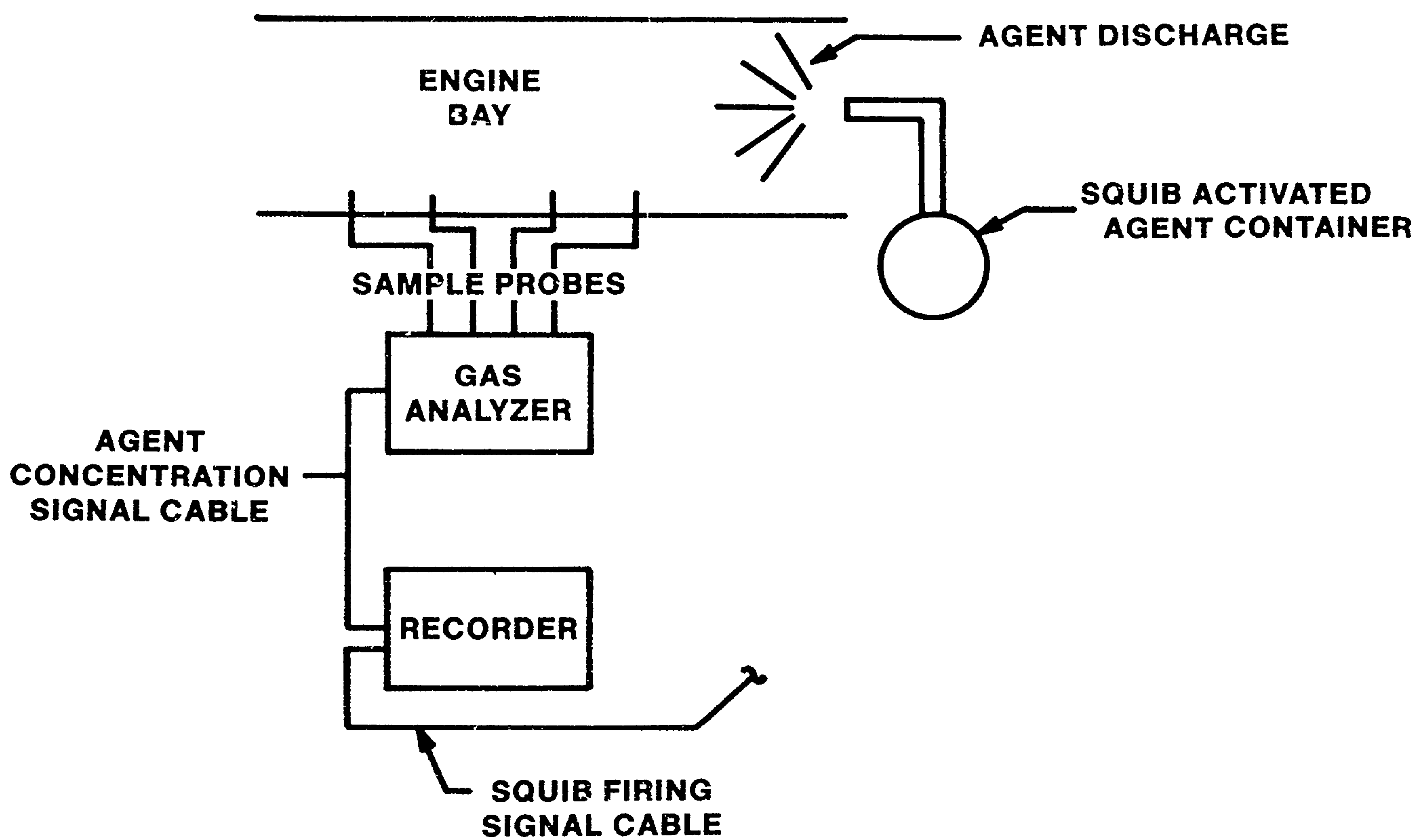


FIGURE 5. SCHEMATIC OF HALON AGENT GAS SAMPLING SYSTEM

TF-30 ejector pumping. In actual service, the ejector-induced airflow occurs automatically when the weight of the aircraft is on the main landing gear wheels and the engine is operating. The actual ejector-induced ventilation rate was not known, since only a portion of the airflow was measured, i.e., that air entering the nacelle via the secondary air inlet duct. During ejector pumping operation, air can enter the nacelle by a number of possible paths, which include not only the secondary air inlet duct, but also fire access doors and around nacelle door and panel seams. The facility instrumentation measures only that air entering the nacelle through the facility ducting into the secondary air inlet. Table 1 shows the ejector-induced ventilation rates for various engine power settings for the F-111.

TABLE 1. F-111A EJECTOR INDUCED VENTILATION RATE*

Power ($\% N_2$)	Ejector Pumping (Lb/Sec)	Remarks
65	3.93	Idle
70	4.26	
77	4.66	
85	4.83	
89	5.0	Military power
Zone 1-A/B	5.26	
Zone 3-A/B	7.6	
Zone 5-A/B	5.66	

* Information provided by General Dynamics

No such information was available for the EF-111, but these values are presumed to be representative for this aircraft as well. Tables 2 and 3 show typical ventilation rates at various flight conditions for the F and EF-111 aircraft. Note that nacelle mass airflows and Mach numbers are different for the same flight condition in the F and EF models.

TABLE 2. TYPICAL NACELLE VENTILATION RATES OF F-111A AIRCRAFT*

Flight Condition	Mach No.	Altitude (Ft)	Ventilation Rate (Lb/Sec)
Cruise	0.75	35000	6.12
Landing Approach	0.2	Sea Level	7.12
Takeoff	0.21	Sea Level	7.32
Holding	0.36	3000	10.05
Sea Level Dash	1.2	Sea level	30.4

* Information provided by General Dynamics

TABLE 3. TYPICAL NACELLE VENTILATION RATES OF EF-111 AIRCRAFT*

Flight Condition	Mach No.	Altitude (Ft)	Ventilation Rate (Lb/Sec)
Cruise	0.75	30000	5.98
Landing Approach	0.23	Sea Level	7.46
Takeoff	0.25	Sea Level	7.94
Holding	0.4	3000	9.67
Sea Level Dash	1.1	Sea Level	22.3
Special	0.6	20000	7.15

* Information provided by General Dynamics

See figure 6 for the Halon 1202 concentrations for test no. FOC-1 and table 4 for the summary of individual test conditions. Using the criteria of 6 percent agent concentration for not less than 0.5 second at all locations simultaneously throughout the nacelle, figure 6 indicates that the extinguishing system was adequate in the aircraft parked/engine operating test condition. The cross-hatched rectangle in this figure, which denotes 6 percent volumetric concentration for 0.5 second, fits totally under all agent sampling probe plots, thus indicating compliance with accepted criteria and, therefore, an acceptable system for this test condition.

2.2.2 Test No. FOC-2 (Cruise)

This test simulated a Mach 0.75 cruise condition at 35,000 feet for the EF-111 aircraft. As noted in table 4 the target ventilation rate for this test was 5.98 lb/sec. Due to the sensitivity of the air supply duct pressure transducers and turbulence encountered in the air supply duct, there was fluctuation in the indicated ventilation mass flow reading. The YTF-33 air supply engine throttle and the duct flow-regulator gate were positioned to yield a flow rate that generally fluctuated above and below the target. In this instance, the rate recorded was between 5.3 and 6.0 lb/sec. This procedure was followed for all tests requiring forced ventilation.

See figure 7 for the recorded Halon 1202 concentrations for test no. FOC-2 and table 4 for the summary of test conditions. Figure 7 shows that the extinguishing system did not meet the recommended minimum concentration and time requirements for an acceptable system. Although the level of agent concentration exceeded 6 percent at all probe locations individually at some time subsequent to agent discharge, it did not persist at this level at all probe locations simultaneously throughout the nacelle for a period of 0.5 second. Thus, while all probes individually received concentrations adequate to extinguish a fire at their location, the possibility of reignition exists since this event did not occur simultaneously at all locations. The cross-hatched rectangle in this figure shows that only slightly more than 2 percent volumetric concentration was recorded simultaneously at all probe locations for the specified 0.5 second.

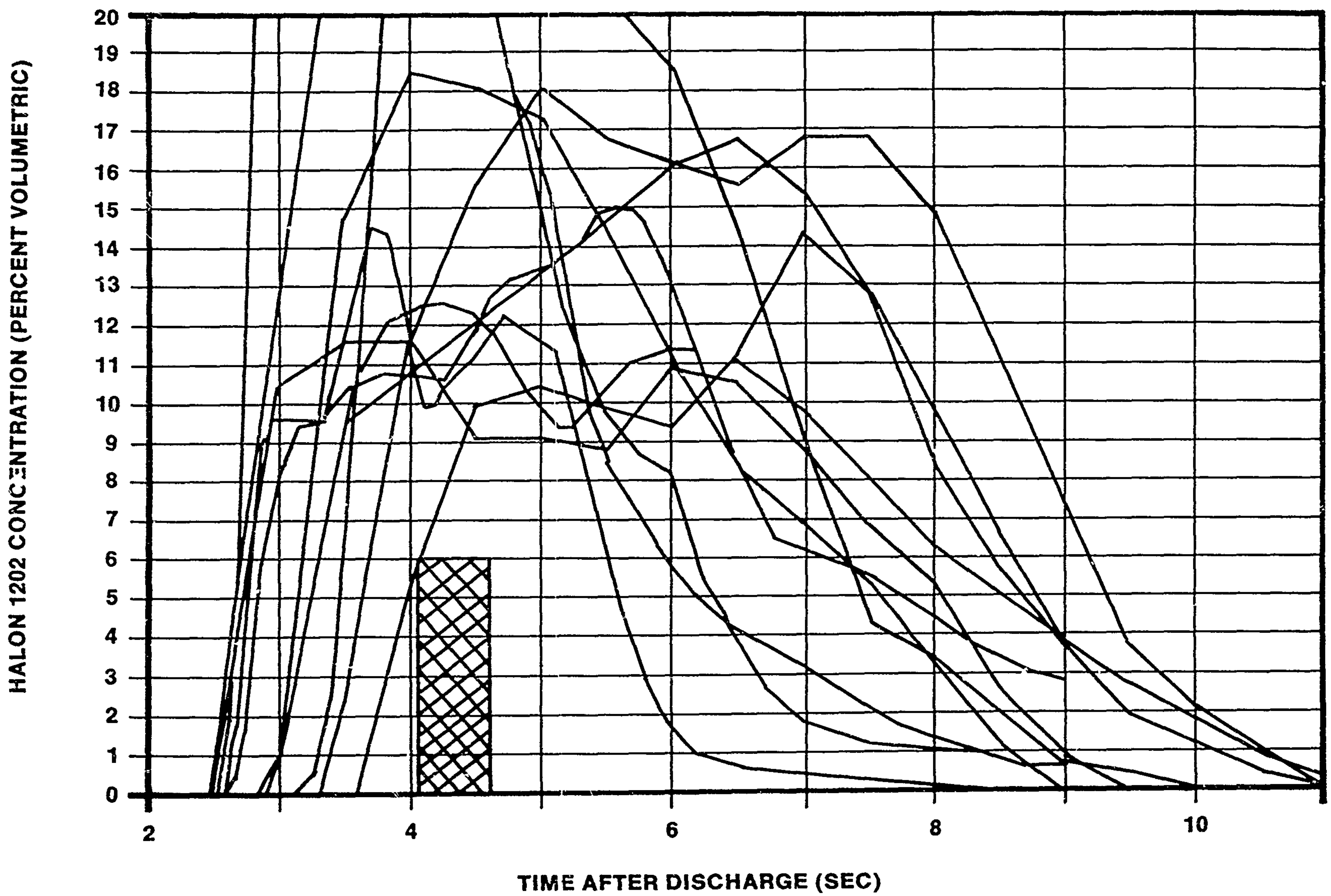


FIGURE 6. AGENT CONCENTRATIONS FOR TEST NO. FOC-1: AIRCRAFT PARKED/ ENGINE OPERATING

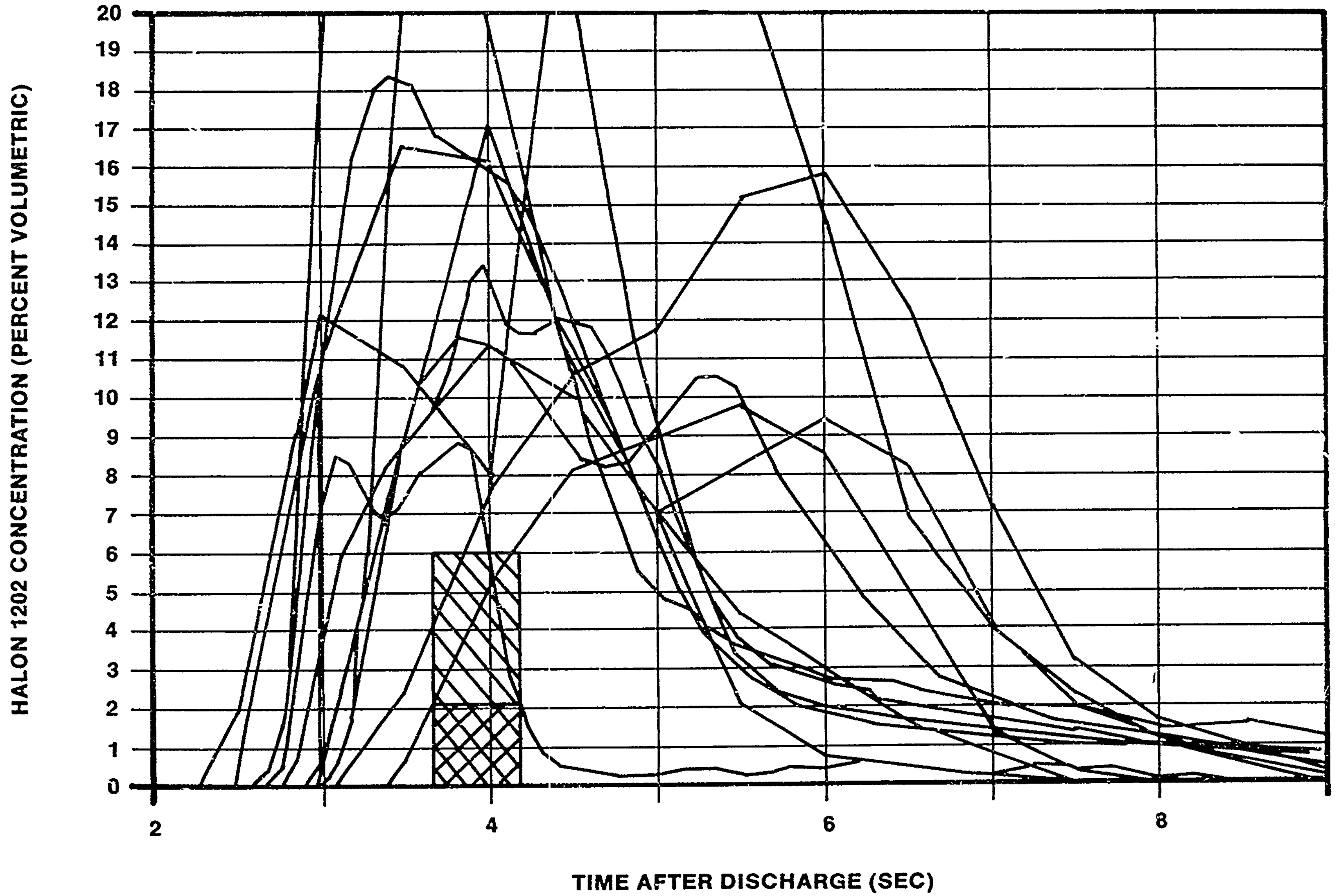


FIGURE 7. AGENT CONCENTRATIONS FOR TEST NO. FOC-2: CRUISE

TABLE 4. SUMMARY OF TEST CONDITIONS

Test No.	Target Ventilation Rate (Lbs/Sec)	Measured Ventilation Rate (Lb/Sec)	Ejector Pumping	Maximum TF-30 Throttle Prior to Chop	Simulated Test Condition
		EF-111 Aircraft			
FOC-1	(1)	(2.4/2.9) (2)	Yes	90%	Ground Static
FOC-2	5.98	5.3/6.0	No	80%	Cruise
FOC-6	22.3	22.1/22.8	No	Zone 1-A/B	Sea Level Dash
FOC-7	7.15	6.6/7.7	No	85%	Mach 0.6 @ 20K
OC-1	(1)	(2.4/3/2) (2)	Yes	90%	Ground Static
OC-2	7.94	7.6/8.3	No	90%	Takeoff
OC-3	22.3	22.1/23.2	No	Zone 1-A/B	Sea Level Dash
		F-111 Aircraft			
F-1	(1)	(2.3/2.9) (2)	Yes	90%	Ground Static
F-2	10.05	9.8/10.4	No	70%	Holding
F-3	30.4	29.1/31.4	No	Zone 1-A/B	Sea Level Dash

Notes

1. See Table 1
2. Aspirated air measured in secondary air inlet duct; does not represent total air flow.

2.2.3 Test No. FOC-6 (Sea Level Dash)

This test simulated a Mach 1.1 sea level dash flight condition for the EF-111 aircraft. The target ventilation rate was 22.3 lbs/sec. See figure 8 for the Halon 1202 concentrations for test no. FOC-6 and table 4 for the summary of test conditions. During this test, probes 1, 3, and 11 did not at anytime attain levels of 6 percent volumetric concentration. Probe 10 did not attain 6 percent for 1/2-second, and the simultaneous 6 percent reading was not achieved at a number of other probe locations.

2.2.4 Test No. FOC-7 (Special Condition)

This test simulated an EF-111 flight condition of Mach 0.6 at 20,000 feet. The target ventilation rate for this flight condition was 7.15 lb.sec. The measured ventilation rate during this test was 6.6 to 7.7 lb/sec.

See figure 9 for the Halon 1202 concentration for test no. FOC-7 and table 4 for the summary of test conditions. The cross-hatched area of the rectangle inserted in figure 9 indicates that the maximum level of agent concentration that persisted simultaneously throughout the nacelle for 0.5 seconds was approximately 0.5 percent. The remainder of the 6 percent/0.5 second rectangle extends into the concentration data curves indicating the extinguishing system did not meet the recommended minimum requirements in this flight condition.

2.2.5 Test No. OC-1 (Aircraft Parked/Engine Operating)

This test was similar to test no. FOC-1, in that it simulated an aircraft parked/engine operation condition for the EF-111 aircraft. See figure 10 for the Halon 1202 concentration for test no. OC-1 and table 4 for the summary of test conditions. For the OC-series of tests, seven of the agent sampling probes were relocated. For the purpose of this report, the relevant probes in figure 10 are D and G. These two probes indicated concentration in the immediate vicinity of the IDG oil cooler. Probe D was positioned approximately 1-inch forward of the geometric center of the oil cooler and probe E was positioned approximately 1-inch aft of the geometric center of the oil cooler. The D curve is identified by a solid circle symbol and the E curve by a solid square symbol.

It is obvious from the data that the minimum recommended concentration and time criteria is greatly exceeded around the oil cooler. Further, for this test condition, all probe locations in the nacelle exceeded the recommended minimum requirements.

For purposes of expanding the system performance data base, but not relevant to the stated purpose of this section, probes A, B, C, F, and G were located in areas other than those shown in figures 2 and 3. The data acquired at these probe locations are discussed in Section V.

2.2.6 Test No. OC-2 (Takeoff)

This test simulated a takeoff condition for the EF-111 aircraft. Target ventilation rate for this test was 7.94 lbs/sec. See figure 11 for the Halon 1202 concentration for test no. OC-2 and table 4 for the summary of test conditions. As with test no. OC-1, the relevant probes in figure 11 are D and E. As in test no. OC-1, this figure shows that the concentration of agent in the

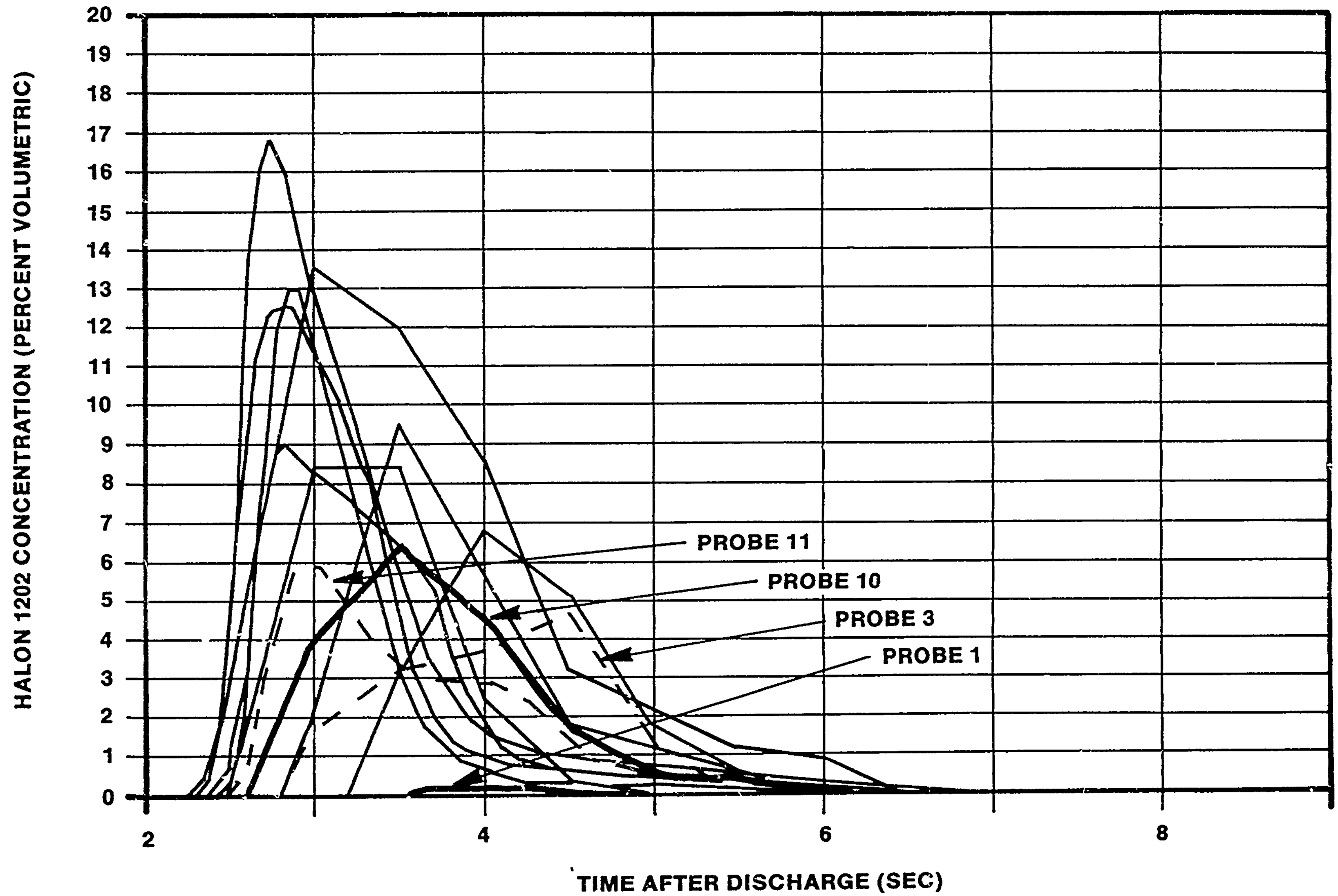


FIGURE 8. AGENT CONCENTRATIONS FOR TEST NO. FOC-6: SEA LEVEL DASH

FIGURE 9. AGENT CONCENTRATIONS FOR TEST NO. FOC-7: SPECIAL CONDITION

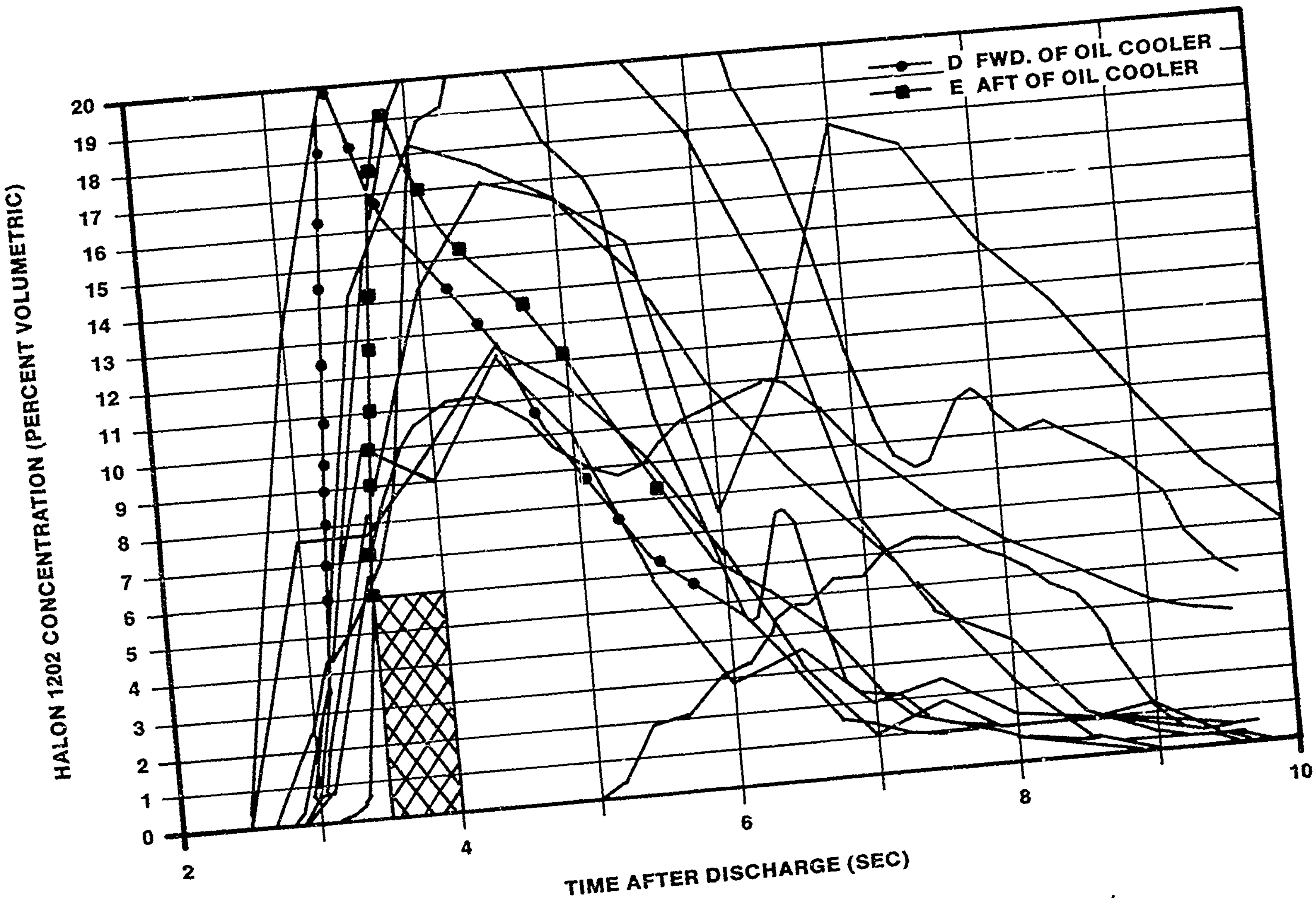


FIGURE 10. AGENT CONCENTRATIONS FOR TEST NO. OC-1: AIRCRAFT PARKED/ ENGINE OPERATING

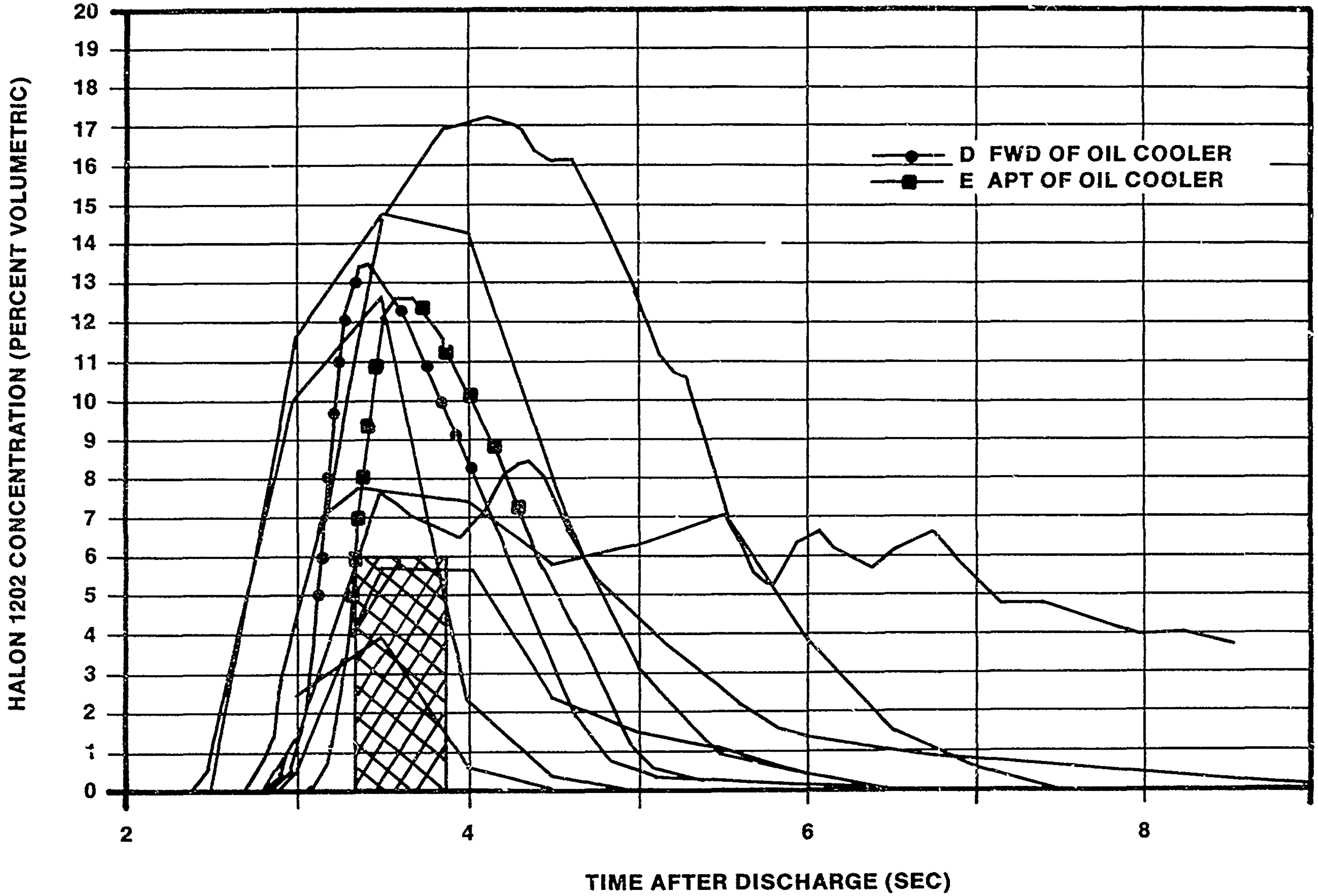


FIGURE 11. AGENT CONCENTRATIONS FOR TEST NO. OC-2: TAKEOFF

area of this cooler exceeds 6 percent for the required 0.5 second, although the peak concentration and time above 6 percent were greatly reduced. Thus, the extinguishing system does provide adequate fire protection in the vicinity of the oil cooler in the takeoff condition. However, as indicated in the discussion of FOC-2 test results, the extinguishing system failed to meet the recommended minimum criteria for the overall nacelle. Although test FOC-2 was not the same simulated operation condition, the ventilation rate was lower (5.98 versus 7.94 lbs/sec) and thus represented a less severe test with regard to agent dilution. The fact that the oil cooler is protected becomes academic when other areas of the nacelle are vulnerable to fire.

2.2.7 Test No. OC-3 (Sea Level Dash)

This test simulated a Mach 1.1 sea level dash flight condition for the EF-111 aircraft. Target ventilation rate for this test was 22.3 lbs/sec. See figure 12 for the Halon 1202 concentration for test no. OC-3 and table 4 for the summary of test conditions. The relevant IDG oil cooler probes in figure 12 are again D and E. The cross-hatched rectangle inserted in this figure pertains to curves D and E only. It indicates that for a time increment of 0.5 second, the maximum agent concentration that persisted around the oil cooler was approximately 3 percent. This did not meet the 6 percent minimum requirements, and thus the extinguishing system did not provide adequate fire protection for the oil cooler in the sea level dash flight condition.

The ventilation rate for test no. OC-2 was about 8 lb/sec and for OC-3 was about 22.5 lb/sec. Somewhere between the two ventilation rates, the system falls below the minimum concentration/time criteria around the oil cooler. Using figures 10, 11, and 12 an attempt was made to extrapolate the duration at which a 6 percent level of agent concentration would be maintained in the area of the oil cooler. That extrapolated data is shown in figure 13. This figure is presented merely to show a trend; and that trend, as expected, is that the duration at which a 6 percent level of agent concentration can be maintained diminishes as ventilation rate increases. Figure 13 appears to indicate that for a 0.5 second duration, the level of agent concentration will fall below 6 percent at a ventilation rate of 13 lb/sec. This estimation is only of academic interest since the extinguishing system failed to meet the criteria for the overall nacelle at the cruise condition (FOC-2), which was at a much lower ventilation rate than 13 lbs/sec.

2.2.8 Test No. F-1 (Aircraft Parked/Engine Operating)

The F-series of tests were conducted to gain a basic insight into the performance of the F-111A extinguishing system. Sampling probes were again located as in the FOC-series tests and the original 1969 test. The IDG oil cooler and lines were removed from the nacelle. Test F-1 simulated the aircraft parked/engine operating ground condition with ejector pumped nacelle airflow. The test results are shown in figure 14 and indicate that the system again met the recommended minimum requirements in this test condition. The test conditions are shown in table 4.

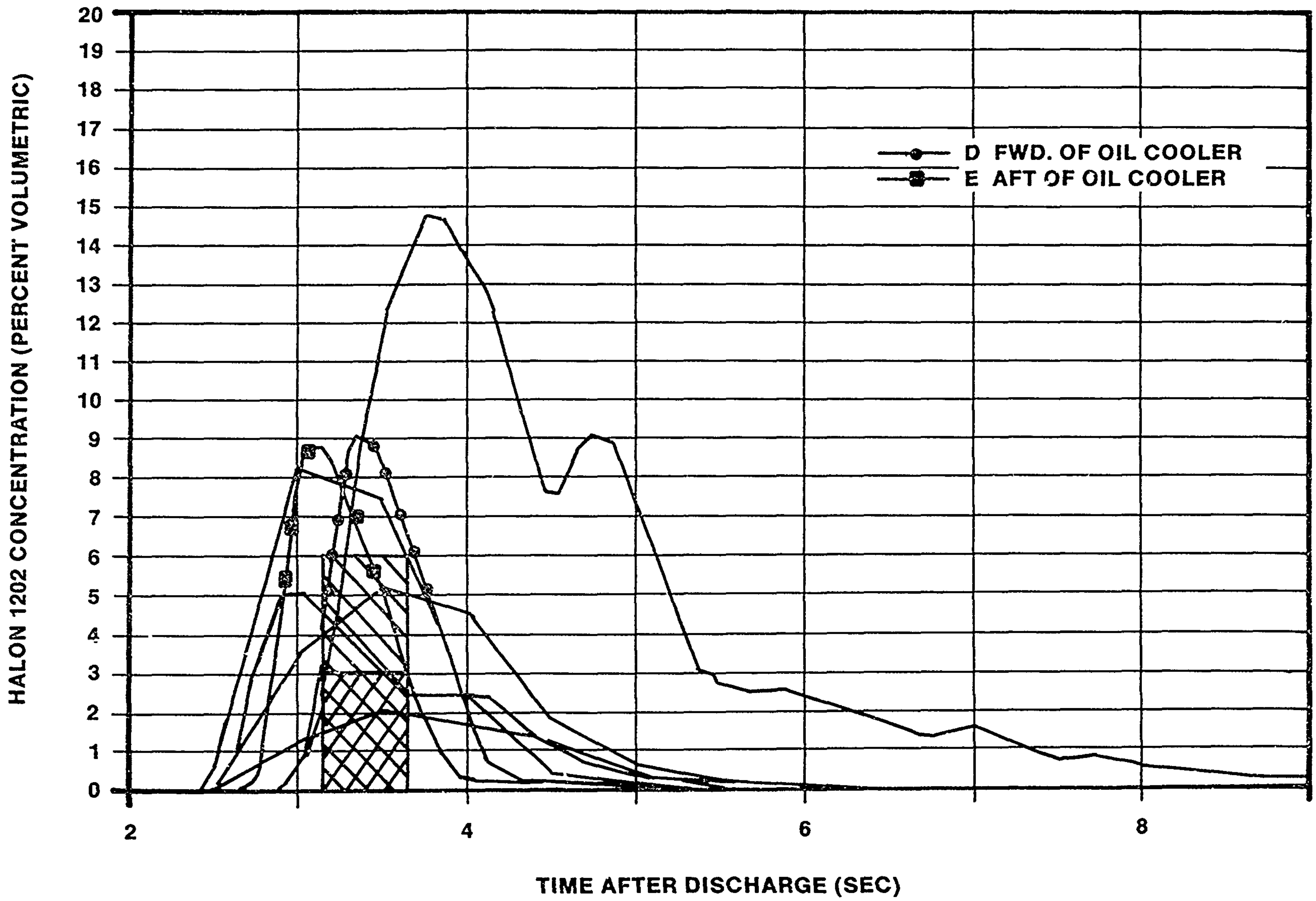


FIGURE 12. AGENT CONCENTRATIONS FOR TEST NO. OC-3: SEA LEVEL DASH

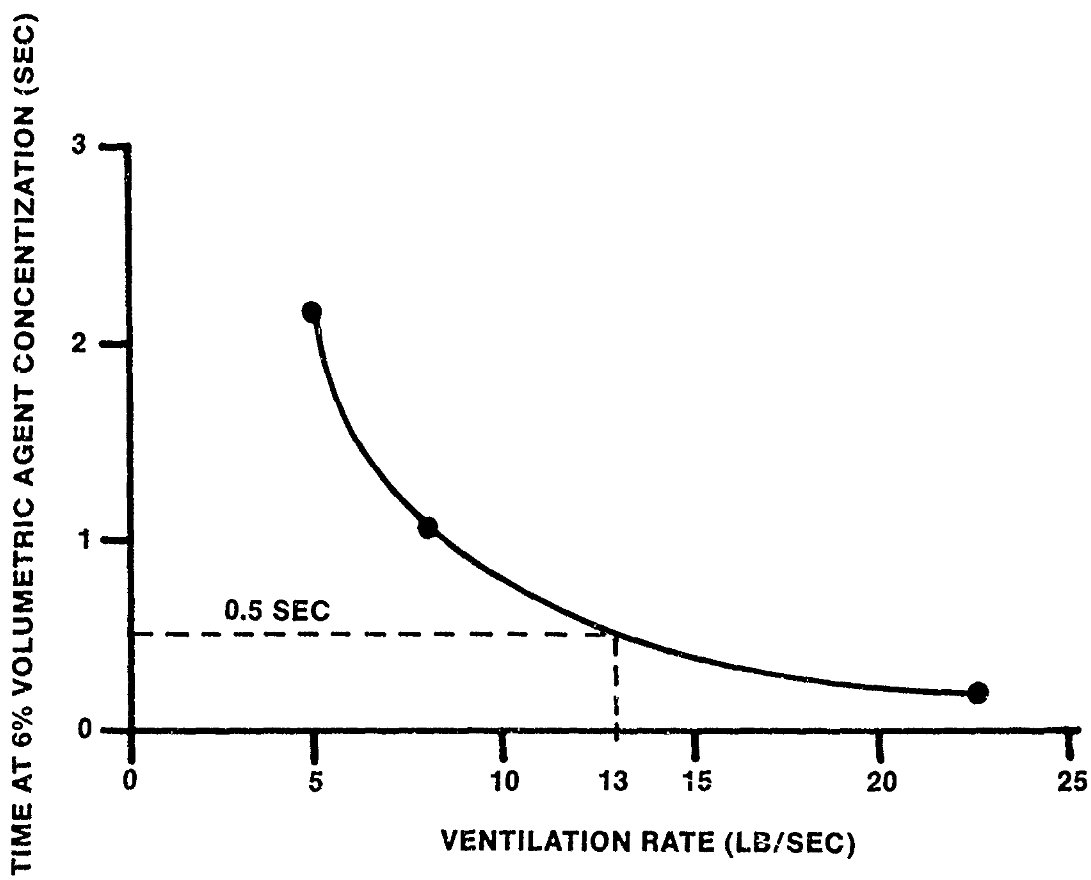


FIGURE 13. APPARENT EFFECT OF VENTILATION ON AGENT CONCENTRATION IN AREA OF OIL COOLER

FIGURE 14. AGENT CONCENTRATIONS FOR TEST NO. F-1: AIRCRAFT PARKED/ ENGINE OPERATING

2.2.9 Test No. F-2 (Holding)

This test simulated a Mach 0.36 holding condition at 3,000 feet for the F-111A aircraft. Target ventilation rate was 10.05 lbs/sec. The test results are presented in figure 15, and the test conditions are shown in table 4. The test results indicate that the recommended minimum requirements for an acceptable system were not met in this flight condition.

2.2.10 Test No. F-3 (Sea Level Dash)

This test simulated a Mach 1.2 sea level dash condition for the F-111A aircraft. Target ventilation rate was 30.4 lbs/sec. The test results are presented in figure 16, and the test conditions are shown in table 4. The test results indicate that the recommended minimum requirements for an acceptable system were not met in this flight condition.

2.3 EFFECT OF VENTILATING AIR

The data contained in this section of the report reveals the significant effect that nacelle ventilation rate has on agent distribution, concentration, and dwell time. This effect warrants additional discussion to illustrate the limitations of the current F-111 nacelle fire extinguishing system.

Figure 17 shows the effect of ventilation rate specifically at the location sampled by probe no. 1. This location was selected since this area of the F-111 nacelle appears to be most affected by changes in ventilation. Each curve on this figure represents the time versus concentration as recorded in the upper forward nacelle area. Note that in the aircraft parked/engine operating ground condition, nacelle ventilation is accomplished by ejector pumping and not by ram air effect as in all flight conditions. As the airflow through the nacelle increases from the aircraft parked/engine operating ground condition to sea-level dash, both the peak concentration and agent dwell time diminish rapidly. At some point between cruise (6 lbs/sec) and holding (10 lbs/sec) this area transitions from receiving acceptable concentration/time readings to unacceptable readings. And the 10 lb/sec holding ventilation rate is only one-third of the 30 lb/sec ventilation rate attainable by the F-111 in the sea-level dash. At the sea-level dash condition for both the F and EF model aircraft, the presence of Halon 1202 is virtually non-existant in this area of the nacelle. For the EF-111, which has a lower sea-level dash ventilation rate than the F-111, the maximum recorded concentration in this area was less than one percent.

Figure 18 depicts the effect of nacelle ventilation when taking into account the nacelle volume sampled by all twelve probes. Based upon the 0.5 second dwell time specified in MIL-E-22285, the test graphs were examined, and the maximum level of agent concentration that existed at all 12 probes simultaneously for not less than 0.5 second was determined. Of the ventilation rate data points on this curve, only the one representing the lowest rate is not a measured value. This point occurred in the aircraft parked/engine operating condition where nacelle ventilation is induced by ejector pumping, and was not directly measurable with the facility instrumentation. The flow was estimated at 4 lbs/sec based upon data obtained from General Dynamics. Figure 18 readily illustrates the adverse effect nacelle ventilation has on agent concentration with the current system in this aircraft. This figure further illustrates that for any ventilation rate beyond approximately 5 lbs/sec, the current system will apparently be unable to provide the 6 percent concentration criteria.

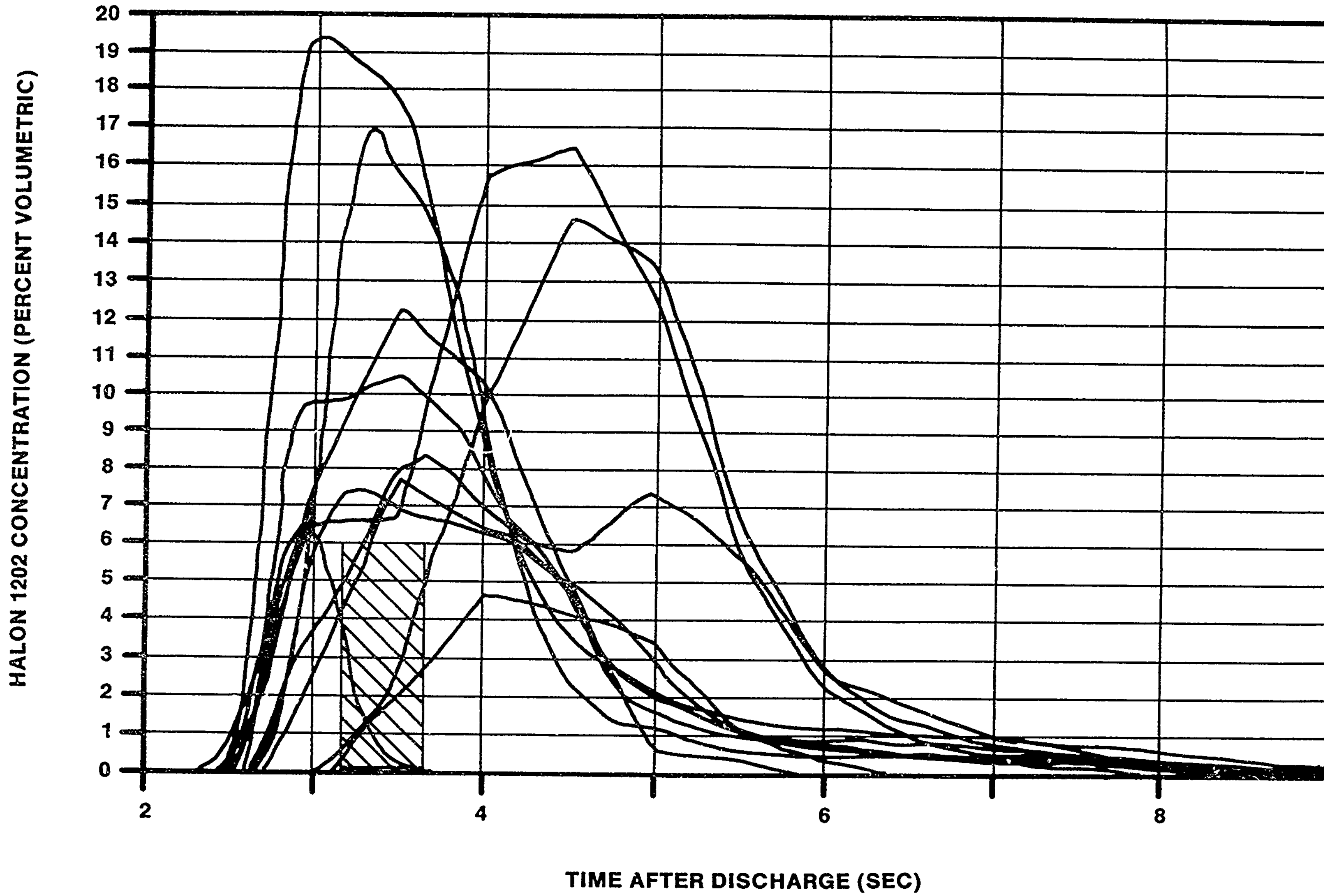


FIGURE 15. AGENT CONCENTRATIONS FOR TEST NO. F-2: HOLDING

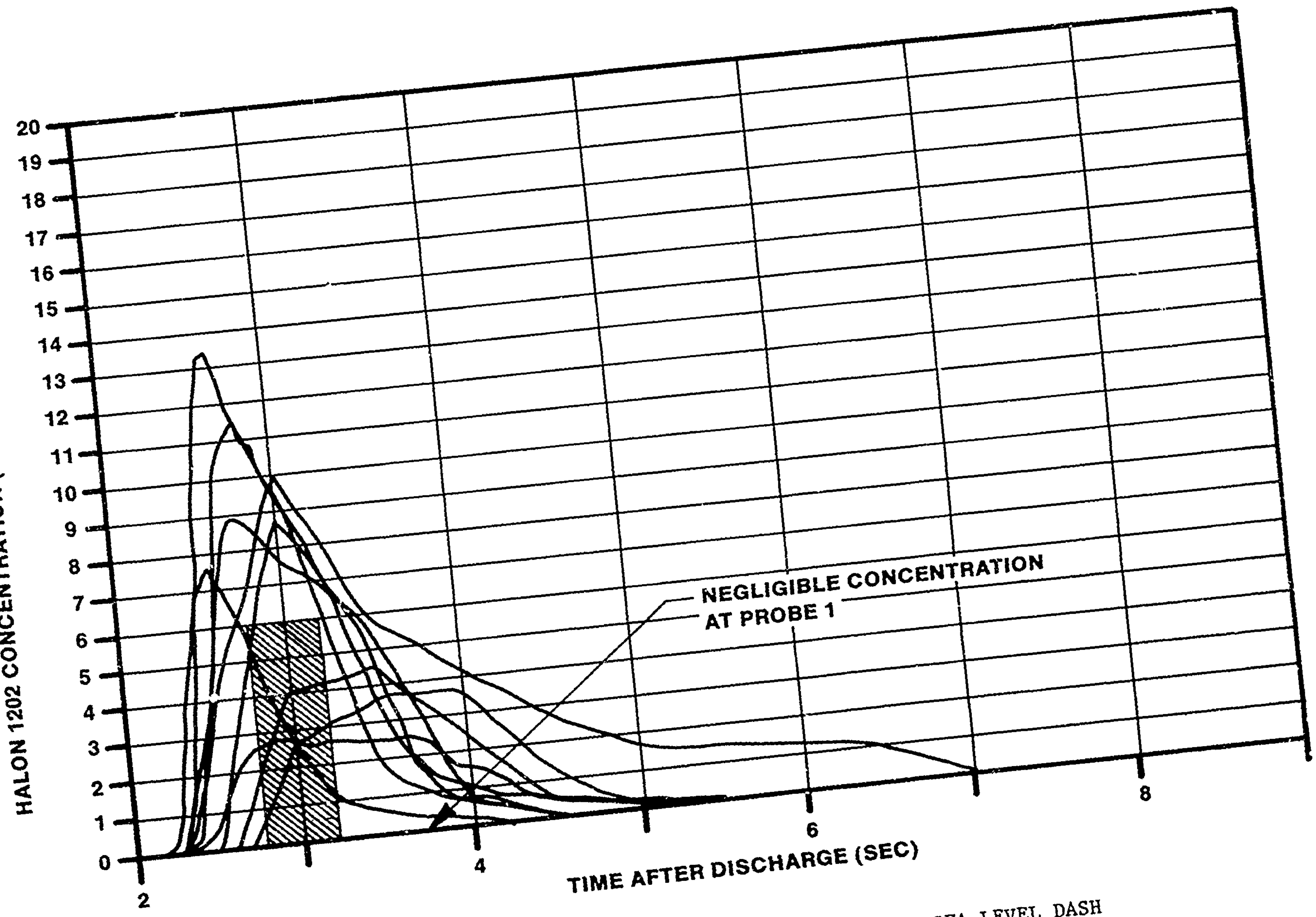


FIGURE 16. AGENT CONCENTRATIONS FOR TEST NO. F-3: SEA LEVEL DASH

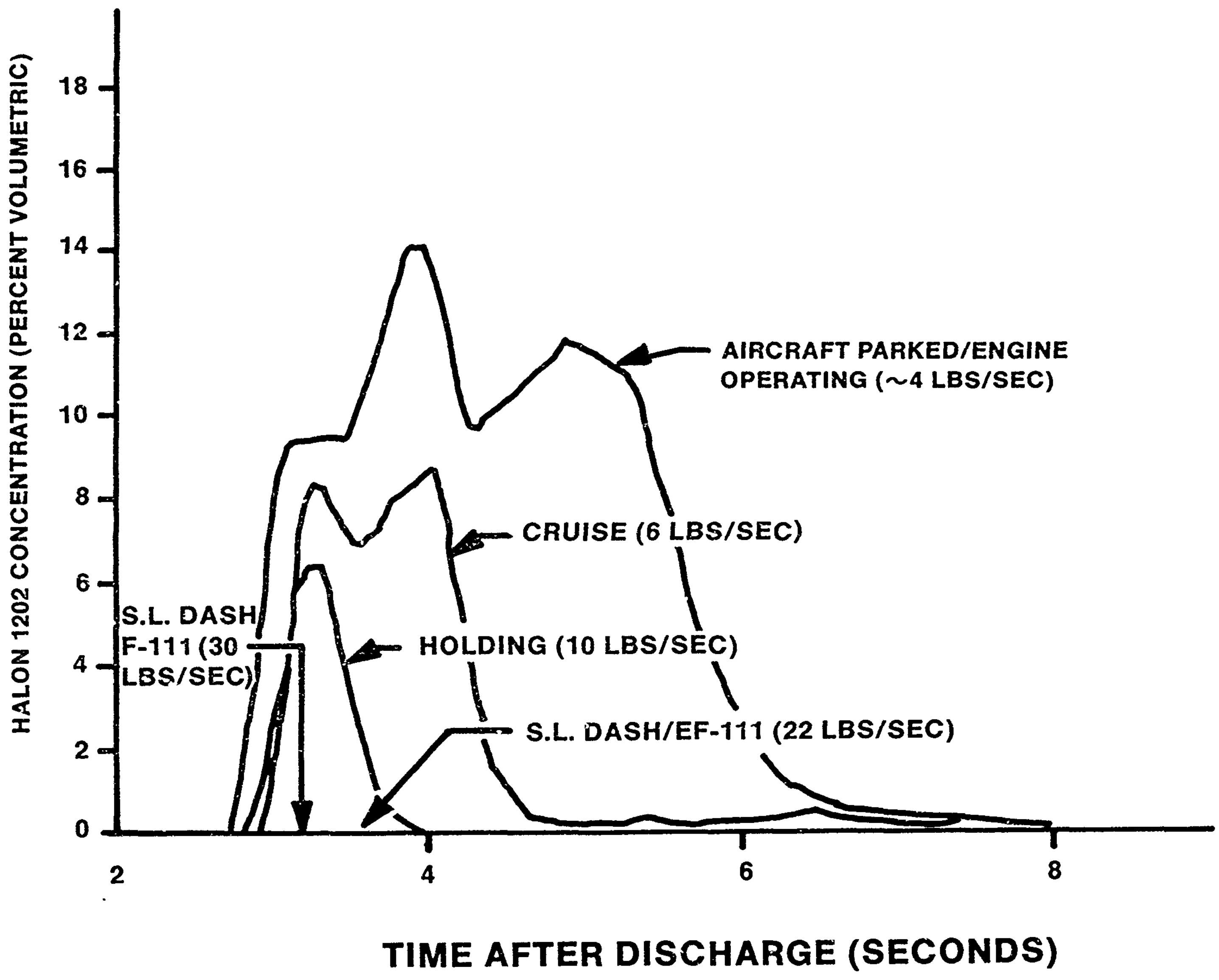


FIGURE 17. EFFECT OF VENTILATION AT PROBE NO. 1

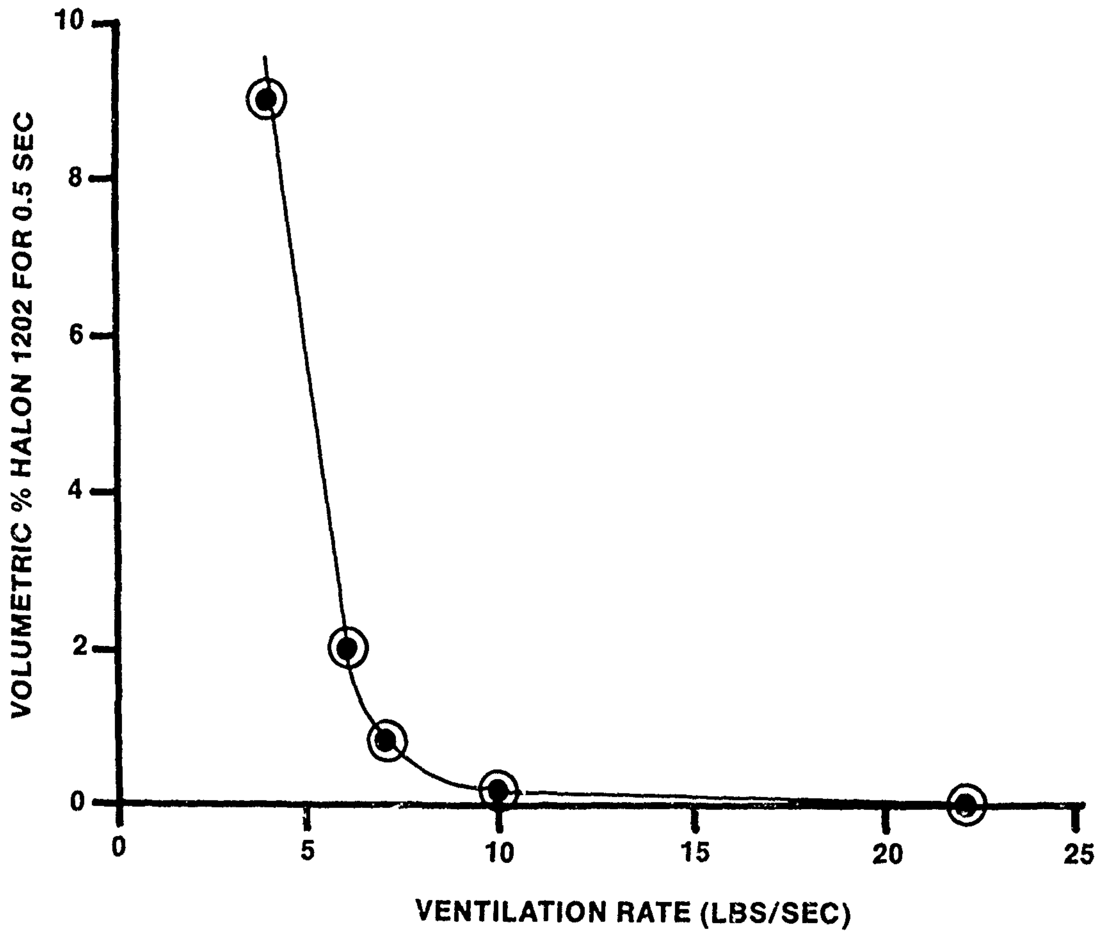


FIGURE 18. EFFECT OF VENTILATION ON OVERALL CONCENTRATION

2.4 ADDITIONAL COMMENTS

The tests reported herein indicate that when using a criteria of 6 percent Halon 1202 concentration persisting simultaneously at all locations throughout the nacelle for not less than 0.5 second, the EF-111 fire extinguishing system is adequate for the aircraft parked/engine operating ground condition. However, at the simulated flight conditions tested, this criteria was not met. In addition, at the sea level dash flight condition, the forward portion of the nacelle indicated virtually no measurable agent concentration. Similarly, at the sea level dash condition for the EF-111 aircraft, the concentration of Halon 1202 that persists around the oil cooler for 0.5 second is approximately 3 percent. Based upon the criteria of 6 percent concentration for 0.5 second at all locations simultaneously, the data acquired during this test program would seem to indicate that the EF-111 nacelle fire extinguishing system is inadequate for virtually all flight conditions.

Although not discussed in the body of this text, liquid Halon 1202 agent was observed exiting the nacelle through seams around the nacelle doors and through the fire access door, which was held partially open by the sampling probes. Consequently, whatever quantity of Halon 1202 exited the nacelle as a liquid was wasted, since it did not vaporize inside the nacelle and thus would not take part in the extinguishment process. A more volatile agent such as Halon 1301 or 1211 may prove more effective for the F and EF-111 aircraft nacelle. This topic, however, is complex and would best be addressed in a more comprehensive F/EF-111 extinguishing system study. A portion of that study is contained in Part 2 of this report.

MIL-E-22285 applies only to Halon 1301 and only to the normal cruise condition. Obviously there are other viable Halon agents, such as 1202 and 1211, which offer advantages in certain aircraft applications and, therefore, should be addressed in the specification. More significantly, the data in this section indicated that acceptance testing in only the normal cruise condition, or in any single condition, may not adequately define the ability of an extinquishing system to successfully combat a nacelle fire. Another speculative point raised during the testing was the effect the post-acceptance test removal of the forward firewall flapper doors had on extinguishing system performance. Of further concern is the fact that the original acceptance testing of the F-111 nacelle extinguishing system was not conducted in as severe a condition as normal cruise. Consideration should be given to nacelle airflows over the entire operational envelope of the aircraft.

SECTION III

CONCLUSIONS

1. The current EF-111 nacelle fire extinguishing system provides adequate fire protection for the area immediately surrounding the IDG oil cooler in the aircraft stationary/engine operating ground condition and in any flight condition having nacelle secondary mass airflows of up to eight pounds per second. This area will not receive adequate fire protection at some undetermined airflow between 8 and 22.3 pounds per second.

2. The current F-111A and EF-111 nacelle fire extinguishing system is adequate in the aircraft stationary/engine operating ground condition.

3. The current F-111A and EF-111 extinguishing system does not provide adequate fire protection for a major portion of the aircrafts' operational flight envelope.

4. The results and rationale of the single ground test used to qualify the F-111A nacelle fire extinguishing system in 1969 were not adequate to define the system's performance during an inflight emergency.

5. After system discharge, some portion of the Halon 1202 extinguishant remains in the liquid state, is lost overboard, and does not contribute to the nacelle fire protection.

6. The IDG oil cooler installation does not significantly affect the distribution of the Halon 1202 extinguishing agent within the nacelle.

7. MIL-E-22285 does not adequately define the installation and testing parameters necessary to insure an effective nacelle fire extinguishing system.

SECTION IV

RECOMMENDATIONS

1. To insure adequate nacelle fire protection, the existing Halon 1202, F/EF-111 extinguishing system should be redesigned and/or optimized to provide the recommended minimum requirements of 6 percent volumetric agent concentration at all locations simultaneously throughout the nacelle for not less than 0.5 seconds throughout the aircraft's entire operational envelope.

2. Prior to any system redesign, a comprehensive study should be made of the nacelle fire history of this aircraft. The long service life of this aircraft presents a unique opportunity to incorporate this information into the logical development of an effective system.

3. A study should be undertaken to determine the feasibility of replacing the existing Halon 1202 extinguishing agent with an alternate, more volatile agent such as Halon 1301 or Halon 1211.

4. Any redesigned Halon 1202 system or alternate agent system should be thoroughly tested under full-scale conditions which are fully representative of the entire operational envelope of the F-111A and EF-111 aircraft.

5. The volumetric concentration of Halon 1202 required to insure adequate nacelle fire protection should be defined by the Air Force.

6. MIL-E-22285, titled "EXINGUISHING SYSTEM, FIRE, AIRCRAFT, HIGH-RATE-DISCHARGE TYPE, INSTALLATION AND TEST OF," dated December 11, 1959 (Revised April 1960) should be revised to take advantage of current knowledge and technology.

V ADDENDUM TO PART I

BACKGROUND

Although readily apparent that the aircraft's extinguishing system was inadequate from the 10 tests reported in the preceeding section, four supplemental tests were conducted to expand the data base in the event a system redesign was mandated in the future. The results of these four tests, designated as FOC-4, 5, 8, and 9 are discussed in this addendum and further support the conclusions reached in the preceeding section. A summary of the test conditions and results of the four tests are contained in table 5.

Also discussed in this section, are the data obtained from five ancillary probe locations used in the OC-series tests. For the OC-series tests, two of the original 12 probes were relocated in the vicinity of the oil cooler. Also, since the OC-series test conditions were essentially duplicates of the FOC-series conditions, five more of the original 12 probes were relocated to expand the data base for the forward section of the nacelle. This forward section appeared to be a problem area with regard to agent concentration.

TEST RESULTS

Test No. FOC-4 (Takeoff)

Figure 19 shows the Halon 1202 agent distribution for the simulated takeoff test condition. See table 5 for the summary of test conditions and results for tests FOC-4, 5, 8, and 9. The target ventilation rate was 7.94 lbs/sec. The agent concentration that persisted throughout the nacelle simultaneously for 0.5 second was less than 2 percent. The system did not meet the acceptance criteria for the takeoff test condition. Although the peak concentrations and dwell time as recorded by the individual probes satisfied the criteria, when taken collectively the criteria was not met.

Test No. FOC-5 (Holding)

Figure 20 shows the Halon 1202 agent distribution for the simulated holding test condition. The target ventilation rate was 9.67 lbs/sec. The measured ventilation rate varied between 9.5 and 9.7 lbs/sec. The agent concentration that existed throughout the nacelle simultaneously for second was less the 1 percent. The probes collectively failed to meet the minimum requirements, and several probes failed to meet the requirements individually.

Test FOC-8 (Exploratory)

The results of test FOC-8 are shown in figure 21. This test was investigative in nature and thus simulated no specific point within the F-111 flight envelope. The intent was to compare the results of this test to the results of test FOC-4 to determine the effect of TF-30 operation on agent distribution. Specific areas of interest were the effects of engine heat and exhaust-induced downstream nacelle pressure on agent distribution. For both tests, the target nacelle ventilating airflow was 7.94 lbs/sec, but the TF-30 engine power settings were different. For test FOC-4, the throttle setting immediately prior to chopping to ground idle was 90 percent N_2, while for test

TABLE 5. SUMMARY OF TEST CONDITIONS FOR SUPPLEMENTAL TESTS

Test No.	Target Ventilation Rate (Lbs/Sec)	Measured Ventilation Rate (Lb/Sec)	Ejector Pumping	Maximum TF-30 Throttle Prior to Chop	Simulated Test Condition	Criteria Compliance
FOC-4	7.94	7.3/7.6	No	90%	Takeoff	No
FOC-5	9.67	9.5/9.7	No	78%	Holding	No
FOC-8	7.94	7.6/7.9	No	Idle	NA*	No
FOC-9	0	0	No	Off	NA (Static Dump)	No

*NA = Not applicable

FIGURE 19. AGENT CONCENTRATIONS FOR TEST NO. FOC-4: TAKEOFF

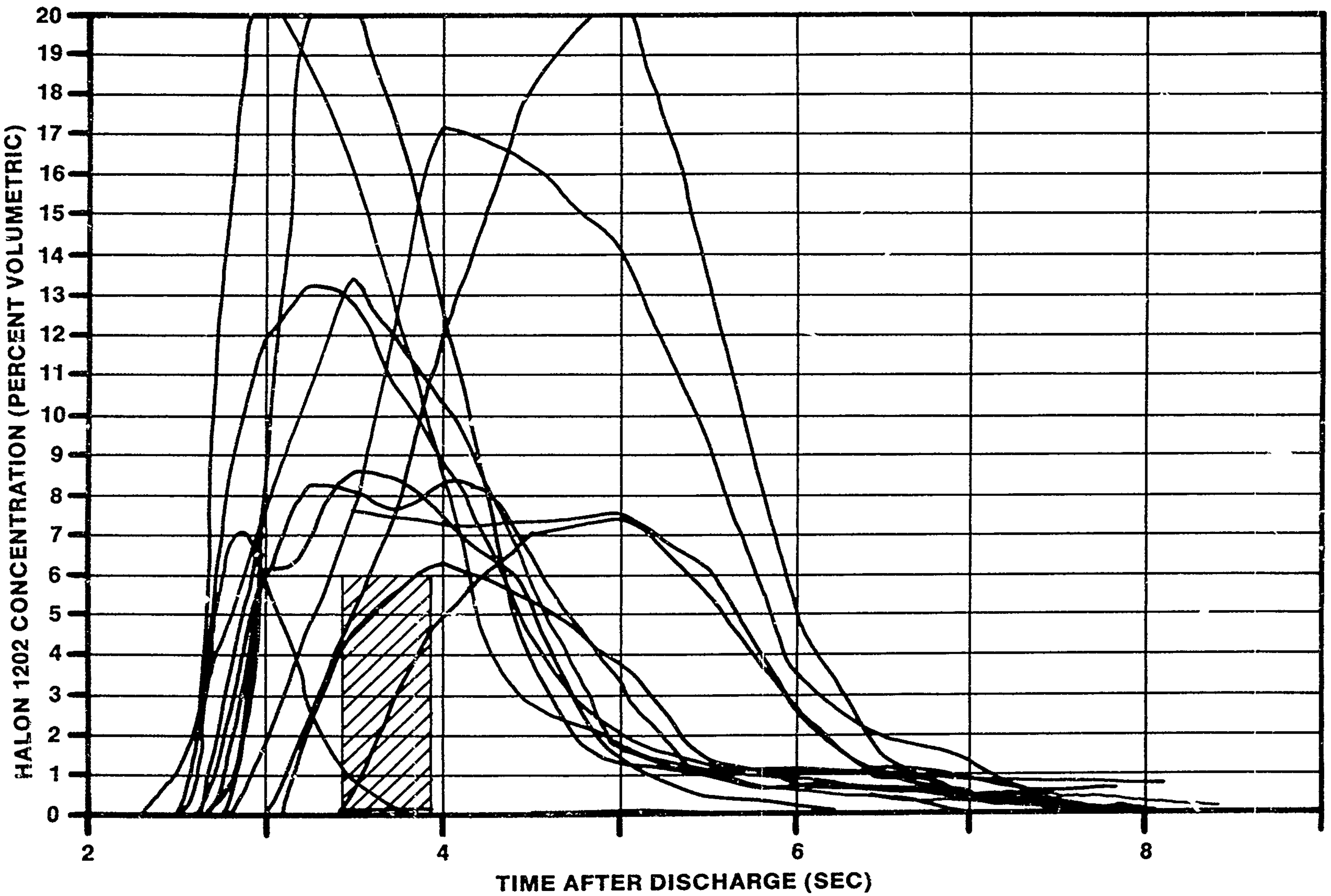


FIGURE 20. AGENT CONCENTRATIONS FOR TEST NO. FOC-5: HOLDING

FOC-8, the throttle setting was maintained at ground idle (65 perc t N_2) with no chop and the ejector pumping system off. Although not completely corroborated by this single test, an individual probe-by-probe comparison of the data indicated that throttle setting may have an effect on agent concentration: The higher throttle setting prior to throttle chop resulted in higher agent concentrations at most probe locations. This extinguishing system did not meet the recommended requirements in this test.

Test FOC-9 (Static Discharge)

Test FOC-9 was also investigative in nature and did not simulate any particular flight or ground operating condition. This was a completely static agent discharge with no forced nacelle ventilation and with the TF-30 engine not operating. The closest emergency situation simulated would be a nacelle fire occurring immediately upon engine startup. The primary purpose of this test, however, was to determine the agent distribution attributable solely to the performance of the aircraft's on-board distribution/nozzle system in the absence of engine heat and airflow. The test results are shown in figure 22 and indicate that the system did not meet the recommended minimum requirements. Note the greatly expanded time scale. The results do indicate uneven system distribution which can be attributed primarily to the discharge nozzle design and positioning. Generally, concentrations at probes located in the upper portions of the nacelle fell off relatively rapidly, since the agent is heavier than air in its vapor state. Concentrations at probes located in the lower portions of the nacelle persisted for greatly extended periods of time due to settling of the undisturbed agent and the suspicion that relatively large amounts of liquid agent collected at the bottom of the nacelle and continued to vaporize long after discharge.

ADDITIONAL COMMENTS FOR TESTS OC-1, OC-2, AND OC-3

In addition to the two probes, D and E, which were placed in the vicinity of the EF-111 IDG oil cooler, five additional probes were relocated in the OC-series tests to provide more information about agent concentration in the forward section of the nacelle. This forward section, which had previously been sampled by only a single probe, was deemed to be a problem area with regard to low agent concentration. Consequently, five new locations were selected and labled as A, B, C, F, and G. See figure 3 for these locations. Probe C was located two inches aft of the firewall in the 6:00 position. At the request of the General Dynamics representative present, Probe G was located 32 inches aft of the firewall in the 6:30 position. Probe G sampled specifically in the vicinity of the primary and utility hydraulic pumps and associated lines and fittings. In all but the engine operating/aircraft parked condition, Probes F and G failed to meet the recommended minimum agent requirements. This was significant, since it confirmed that a much larger volume in the forward section of the nacelle was receiving inadequate agent concentration. Probe C, on the other hand, received extremely high and long-lasting concentrations in all tested conditions, including sea-level dash. It is suspected that this area may be a stagnation area and act as a repository for large quantities of liquid and/or gaseous agent following discharge.

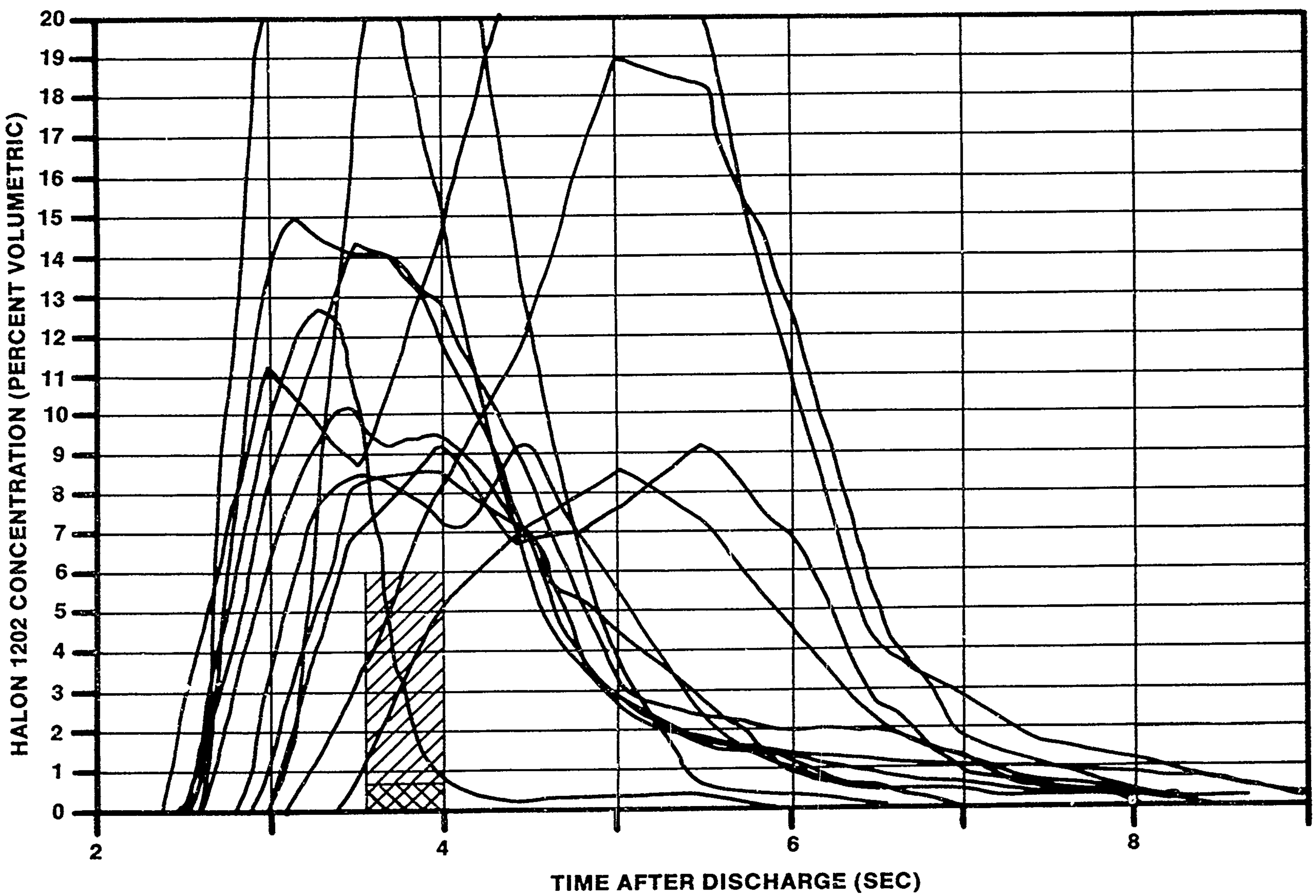


FIGURE 21. AGENT CONCENTRATIONS FOR TEST NO. FOC-8: EXPLORATORY

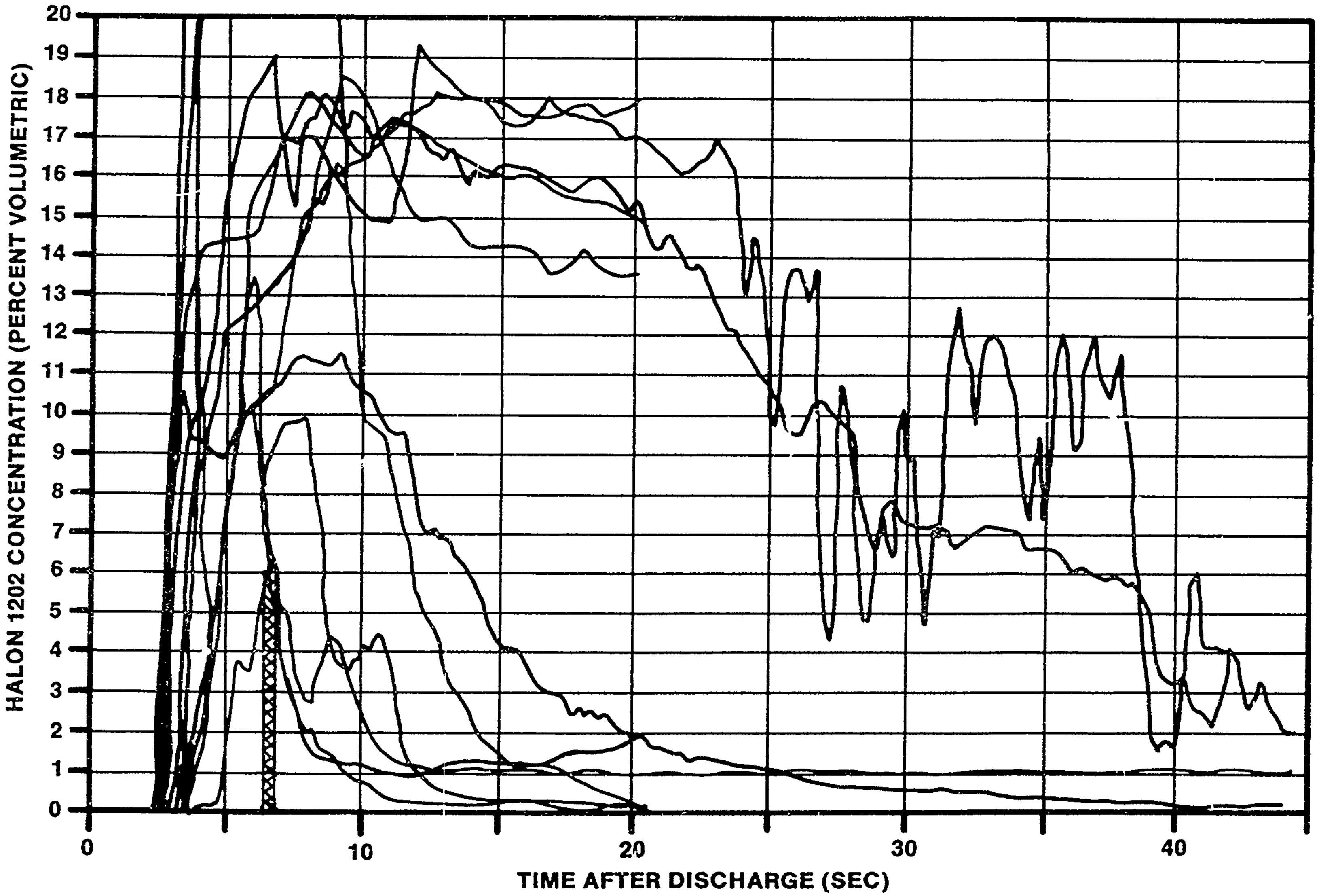


FIGURE 22. AGENT CONCENTRATIONS FOR TEST NO. FOC-9: STATIC DISCHARGE

Probes A and B were located forward of the firewall in the inlet plenum and, thus, were outside the designated nacelle fire zone. This area, therefore, has no built-in fire extinguishing or detection systems. Following discharge in test OC-1, significant quantities of agent were detected in this area. See figure 23 for recorded concentrations at Probes A and B in aircraft parked/engine operation test condition. For purposes of interest only, the 6% by 0.5 second block was inserted in figure 23. In test OC-2, the simulated takeoff condition, a minor, but detectable, quantity of Halon 1202 was recorded at Probe A only. In test OC-3, the sea-level dash conditon, no agent was detected at either Probe A or B.

However, any presence of agent forward of the firewall has an ominous connotation, since if agent can enter this area, so possibly can flammable liquids or vapors. And, as stated, there is no provision to detect a fire in this area. The exact mechanism of agent entry was not determined, but may be due to factors such as suspected reverse airflow in this area, instantaneous overpressure following agent discharge, and the removal of the firewall flapper doors.

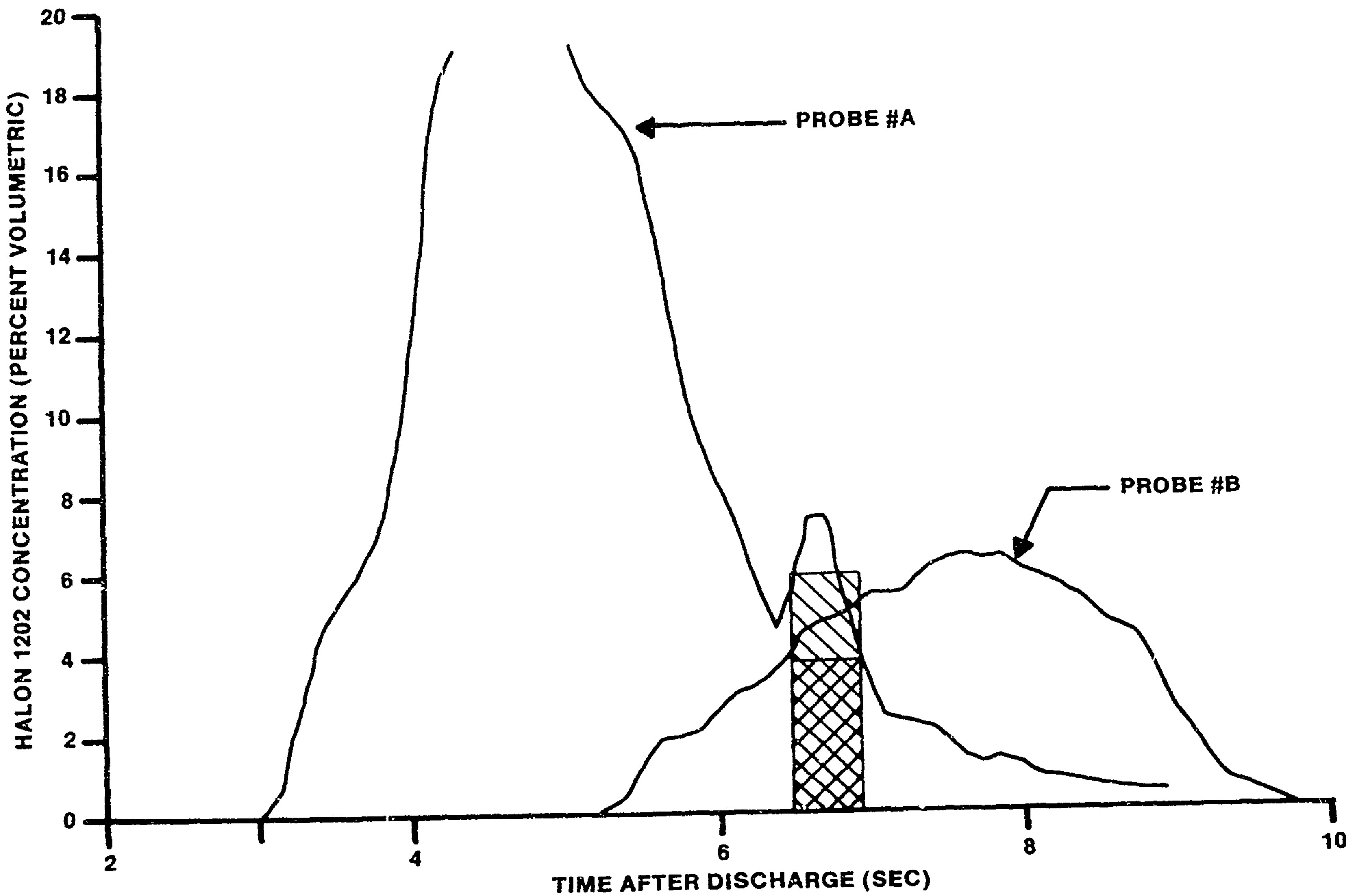


FIGURE 23. AGENT CONCENTRATION AT PROBES A AND B, TEST NO. OC-1

PART 2-HALON 1301 AGENT CONCENTRATION TESTS

VI INTRODUCTION

6.1 PURPOSE

The purpose of this test program was to provide a basic determination of the effectiveness of various quantities of Halon 1301 extinguishant when discharged through the current, on-board, nacelle fire extinguishing system of an F-111 aircraft under simulated flight and ground test conditions. Then, within the constraints of the individual test programs conducted under Part 1 and Part 2, the performance of Halon 1301 and Halon 1202 in the F-111 extinguishing system would be compared.

6.2 BACKGROUND

During the summer of 1986, a test program was completed at the Technical Center in which Halon 1202 was discharged through the on-board extinguishing system into the engine bay of an F/EF-111 aircraft in various simulated flight and ground conditions. The test program is described in Part 1 of this report. The standard, on-board, 385-cubic inch F-111 extinguishing agent container was used for all tests. The agent containers were all filled with 12.65 pounds of Halon 1202 and pressurized with nitrogen to 600 psig. The data from these tests indicated that the current nacelle fire extinguishing system was adequate only for the aircraft parked/engine operating condition. At all other simulated flight conditions, the data indicated that the system was inadequate. The criteria for adequate nacelle fire protection for all tests was a minimum of 6 percent agent concentration existing simultaneously throughout the nacelle for not less than 0.5 second. This criteria was based on MIL-E-22285. The Halon 1202 tests are discussed in Part I of this report.

For all the tests described in Part 2, the agent used was Halon 1301. One factor affecting distribution of the two agents is the significantly lower boiling point, and hence a higher vaporization rate, of Halon 1301. The ambient temperature for a typical Halon 1202 test was in the mid-eighties fahrenheit, whereas the ambient temperature for a typical Halon 1301 test was in the mid-thirties. During the testing with Halon 1202, liquid agent was observed leaking from seams at the bottom of the nacelle. No such condition was observed during the Halon 1301 testing, even though the ambient temperature was much lower.

The Halon 1301 tests were accomplished using three sizes of agent containers holding different weights of extinguishant. In addition to the standard 385-cubic inch F-111 agent container, 630- and 1050-cubic inch spherical agent containers were utilized. The sizes utilized were limited by the availibility of the containers and the required hardware. Due to additional restrictions imposed by unusually severe weather conditions, the specific time period available for testing, and instrumentation and test article engine malfunctions, the scope of the Halon 1301 program was much more limited than that of the Halon 1202 program. The data acquired, however, should provide an adequate foundation for future decisions concerning the F/EF-111 nacelle fire extinguishing system.

6.3 TEST FACILITY

See Part 1, Section 1.1.3 for a description of the facility and test article used for these tests. A primary difference between the facility capability in the Halon 1202 tests and the Halon 1301 tests was the operation of the F-111's TF-30 engine. With one exception, all Halon 1202 tests were conducted with the TF-30 operating. The TF-30 was not operating during the Halon 1301 tests. During engine-start for the first Halon 1301 test, the engine sustained major internal damage which could not be repaired within the allotted test period. The failure eliminated all tests requiring engine induced, ejector pumped, nacelle airflow. This ejector airflow occurs when the weight of the aircraft is on the main landing gear wheels and the engine is operating. Also, with the TF-30 not operating, there was no engine generated heat within the nacelle. Engine generated heat can contribute to agent vaporization and distribution. However, since Halon 1301 has a boiling point of -72° F at normal sea level pressure, the absence of engine generated heat was not considered as significant a factor as it would have been when using Halon 1202, which has a boiling point of 76° F. Nevertheless, the fact that the TF-30 was not operating should be kept in mind when reveiwing the data contained in Part 2, or when comparing the results of Part 1 and Part 2.

As in Part 1, the facility's YTF-33 air supply engine did provide nacelle ventilation for simulation of inflight conditions.

6.4 METHOD OF APPROACH

The objective of the testing was to determine what quantity of Halon 1301, when discharged throught the existing on-board agent distribution tubing, would provide adequate fire protection for the F-111 nacelles. Guidelines from McClellan AFB specified that, for these tests, no changes were to be made to the on-board distribution system, tubing, or discharge nozzles. Only a direct substitution of Halon 1301 for Halon 1202 was to be investigated. The investigation was accomplished, therefore, solely by introducing varying amounts of Halon 1301 into the right-hand nacelle through the existing distribution system at a number of simulated flight conditions. Specified nacelle ventilating airflows were provided for each simulated flight condition by utilizing by-pass fan air from a YTF-33 turbine engine. As noted previously, the aircraft's TF-30 engine could not be operated for this series of tests.

Three different size agent containers were utilized for the tests. These containers were the current, on-board, 385-cubic inch Halon 1202 container; a 630-cubic inch Halon 1301 container; and a 1050-cubic inch Halon 1301 container. All containers were filled with agent at a 50 percent fill ratio to maximize discharge efficiency. The containers were then pressurized with nitrogen to 600 psig. See table 6 for additional container information. Although testing was conducted outdoors in winter, all containers were stabilized indoors at approximately 70° F prior to discharge. It is important to note that in normal service in the F/EF-111 operational temperature environment, the standard Halon 1202 container could not be filled with Halon 1301 and superpressurized with nitrogen due to the extreme difference in vapor pressure of the two extinguishants and the strength of the container.

TABLE 6. EXTINGUISHING AGENT CONTAINER INFORMATION

Container Size (cu. in)	Agent Charge Weight (Lbs)	Nitrogen Charge Pressure (psig)	Fill Ratio	Remarks
385	10.9	600	50%	Std. F-111 Container
630	17.8	600	50%	See Note 1
1050	29.7	600	50%	See Note 2

Notes

1. The container pressure prior to discharge for test 1301-3B indicated 575 psig.

2. The container pressure prior to discharge for test 1301-4A indicated 650 psig.

The standard 385-cubic inch agent container, was installed in its normal position in the F-111. The 630 and 1050 cubic inch spherical containers were mounted external to the aircraft on the test article support structure. For the larger containers, one of the dual outlet parts was plumbed into the aircraft's agent distribution tubing via a 3/4-inch I.D. flexible hose which was 54 inches long. The other outlet port on the container was sealed. All agent containers were discharged electrically by means of an explosive squib and a frangible disc. Installation of the agent containers is shown in figures 24 and 25.

The on-board distribution system was presumably designed as a "high-rate" discharge system using 12.65 pounds of Halon 1202. For a high-rate discharge system, paragraph 3.9 of MIL-E-22285 states that the "... period of time required to discharge the calculated amount of agent shall be one second or less, measured from the time the agent starts to leave the tubing ends until the required amount of agent has been discharged." When using Halon 1301, specifically in the two larger conatiners, no attempt was made to adhere to paragraph 3.9 of MIL-E-22285. Although actual discharge time was not measured, it was aurally preceptable that the larger containers required more time to discharge their contents. Although in apparant conflict with paragraph 3.9, extending the discharge time without lowering peak agent concentrations could be beneficial in the high mass airflow environment in the F-111 nacelle.

The 12 agent sampling probe locations used for the Halon 1301 tests are shown in figure 26. For comparative purposes, the open ends of these probes were positioned in exactly the same locations used for tests designated F and FOC in Part 1 of this report. Due to an instrumentation malfunction, only six gas analyzer channels were available during Part 2. Thus, two duplicate runs were required to record data from all 12 locations. Significant test parameters were closely maintained for each of the two runs that constituted a single test. The criteria for adequate nacelle fire protection was minimum of 6 percent volumetric Halon 1301 concentration recorded at all probe locations simultaneously for not less than 0.5 second. This criteria was based on MIL-E-22285.

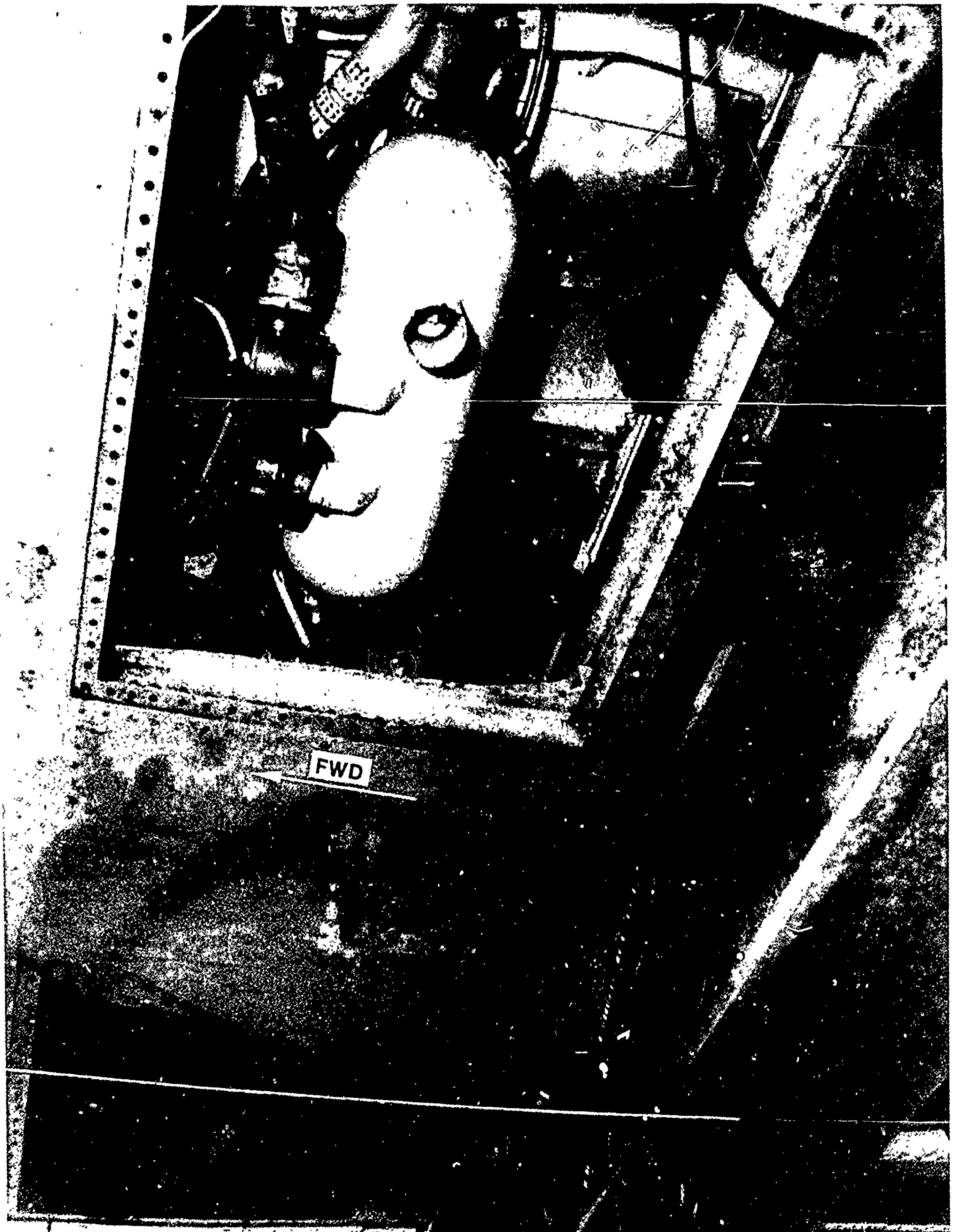


FIGURE 24. INSTALLATION OF STANDARD F-111 AGENT CONTAINER

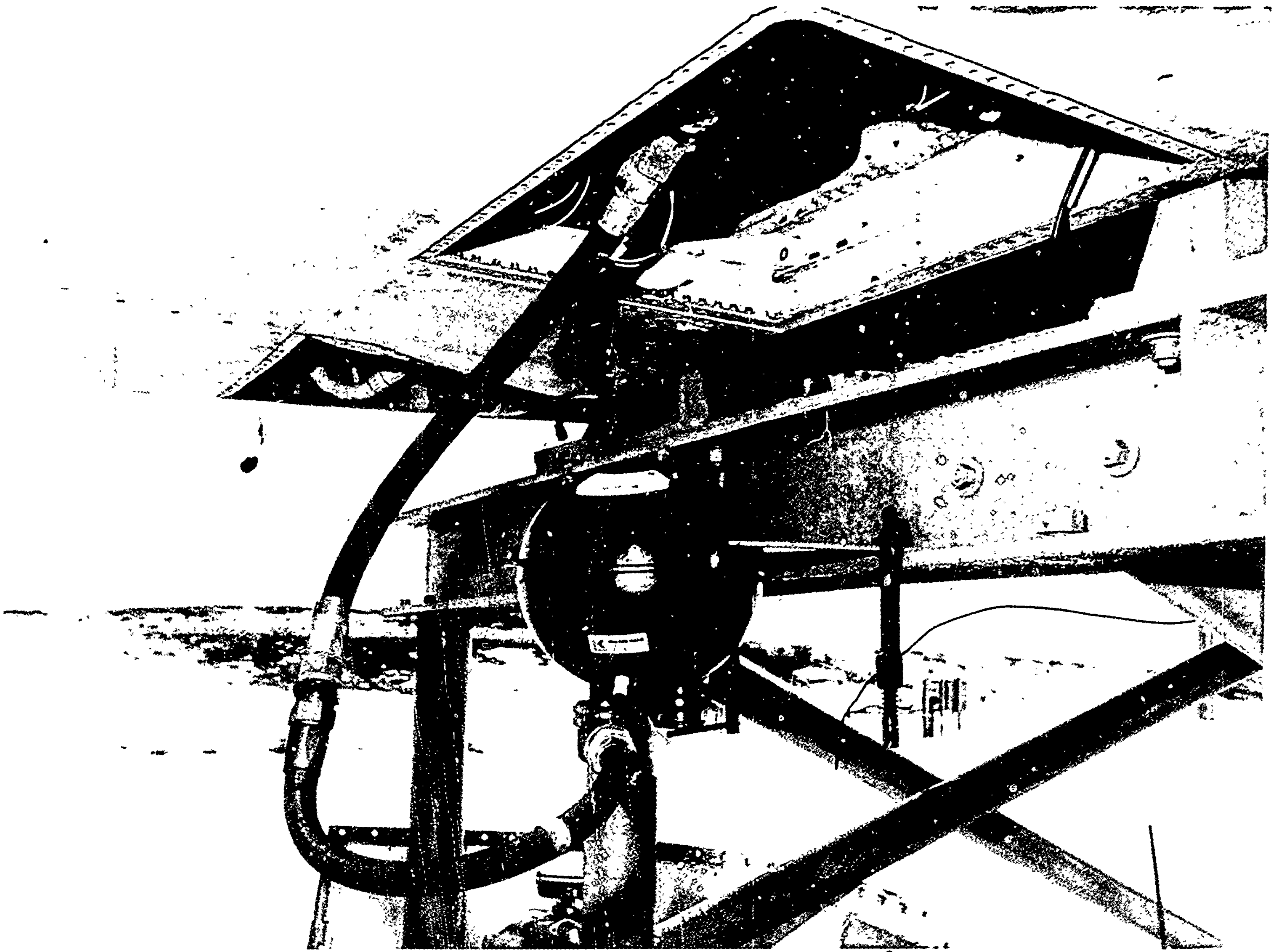


FIGURE 25. TYPICAL TEST INSTALLATION OF 630 AND 1050 IN^3 AGENT CONTAINERS (630 IN^3 CONTAINER SHOWN)

PROBE LOCATIONS

PROBE NO	FUSELAGE STATION	CLOCK* POSITION
1	615	2
2	667	5
3	667	7
4	667	10
5	703	2
6	703	5
7	703	7
8	703	10
9	772	2
10	772	5
11	772	7
12	772	10

*AS VIEWED FROM AFT LOOKING FORWARD

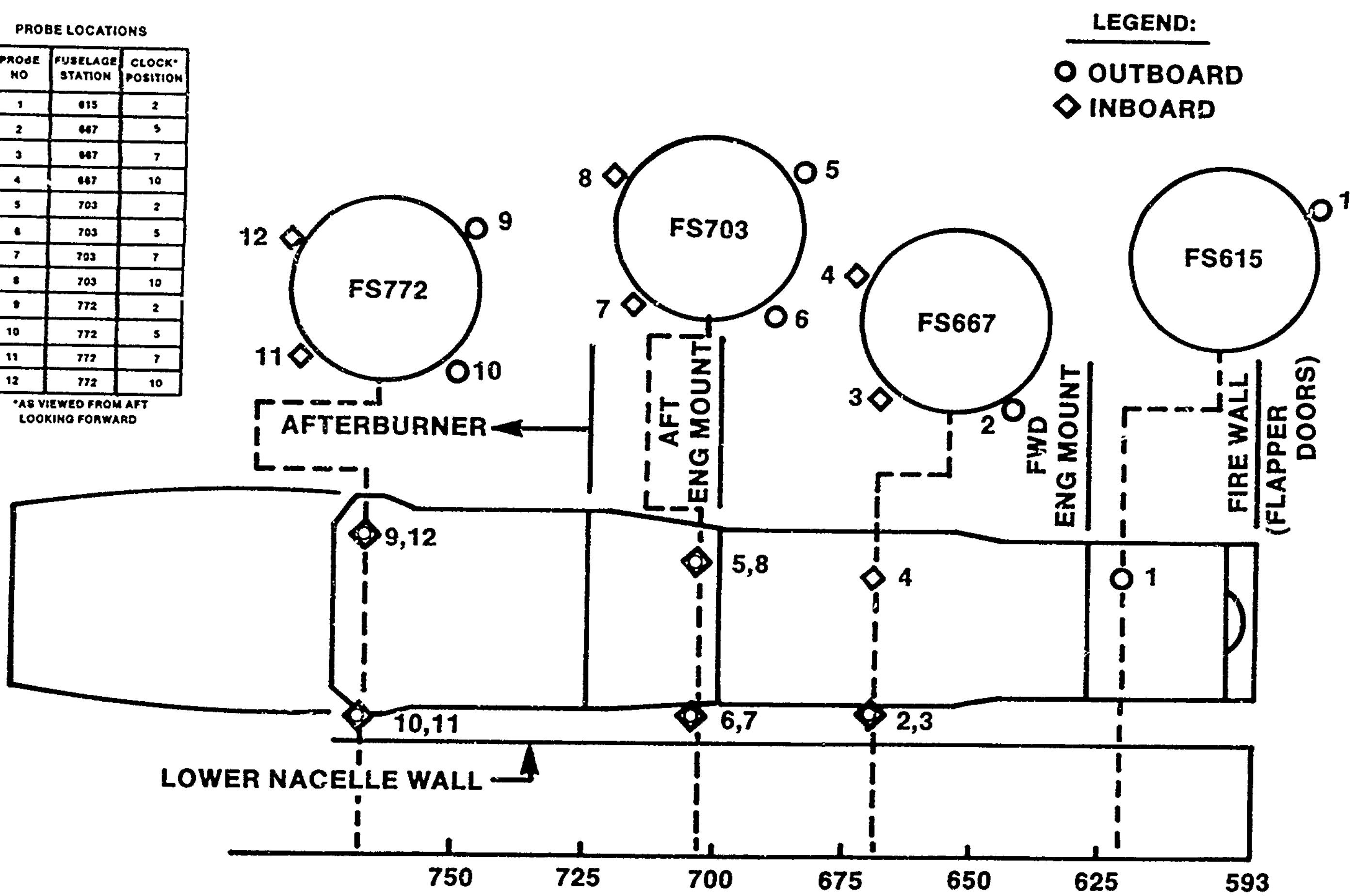


FIGURE 26. OUTBOARD VIEW OF RIGHT-HAND ENGINE SHOWING PROBE LOCATIONS

For each two-run test, the agent containers were filled to precisely the same agent weight and pressure. The nacelle ventilation rate was maintained as closely as facility equipment would allow for both runs of a single simulated flight condition. Figure 27 shows the F/EF-111 extinguishing agent discharge nozzle mounted to the firewall within the nacelle.

6.5 INSTRUMENTATION

The instrumentation for this test program included:

- Beckman Gas Analyzers, Model LB-2, 6 total
- Honeywell Visicorder, Model 1858
- Accurex Ten/10 Datalogger

The Model GA-2A Statham Gas Analyzer used for the Halon 1202 tests was malfunctioning, and, consequently, its use for this program was considered inadvisable. Since only six Beckman Analyzer channels were available, a total of two duplicate runs were required per test to record all 12 probe locations. The 12 probe recording was nesessary for direct comparison with the Halon 1202 tests and also to provide an adequate picture of overall nacelle agent concentration. Agent concentration was recorded on the Honeywell Visicorder, and nacelle ventilation rate was monitered using the Accurex Datalogger.

VII DISCUSSION

7.1 FOREWORD

Subject to three qualifications, the data obtained during this test program is considerd adequate to meet the intended objective. Essentially, that objective was to provide data which would enable the Air Force to make a determination concerning the current F-111 nacelle extinguishing system. The determination would be whether to attempt to modify the existing Halon 1202 system to improve its performance or to pursue an improved system using Halon 1301. The three unplanned qualifying conditions under which the program was conducted were: (1) The absence of engine heat, and perhaps lowered downstream nacelle pressures, generated by the operating TF-30; (2) that each simulated flight condition test consisted of two runs; and (3) that the outside ambient temperature was normally in the mid-thirties Fahrenheit for the Halon 1301 tests and in the mid-eighties for the Halon 1202 tests. With regard to the first qualification, the nacelle ambient temperatures were well above the boiling point of Halon 1301 (-72° F), and therefore, the effect on agent vaporization was considered minimal. Additionally, the charged Halon 1301 containers were allowed to soak in a heated area, and the container temperature was approximately 70° F at the time of testing. No determination can be made concerning the absolute effect of exhaust induced downstream nacelle pressures; however, a limited comparison of data from Part 1 indicated that exhaust velocity had no significant effect on agent distribution. With respect to the second qualification, the two runs which comprised a single test were conducted within minutes of each other, and all factors which would affect distribution were carefully controlled. Close examination of the data and combining the data from the two runs into a single composite figure did not reveal any anomolous conditions that would suggest that this approach was not valid. The third qualification is related to

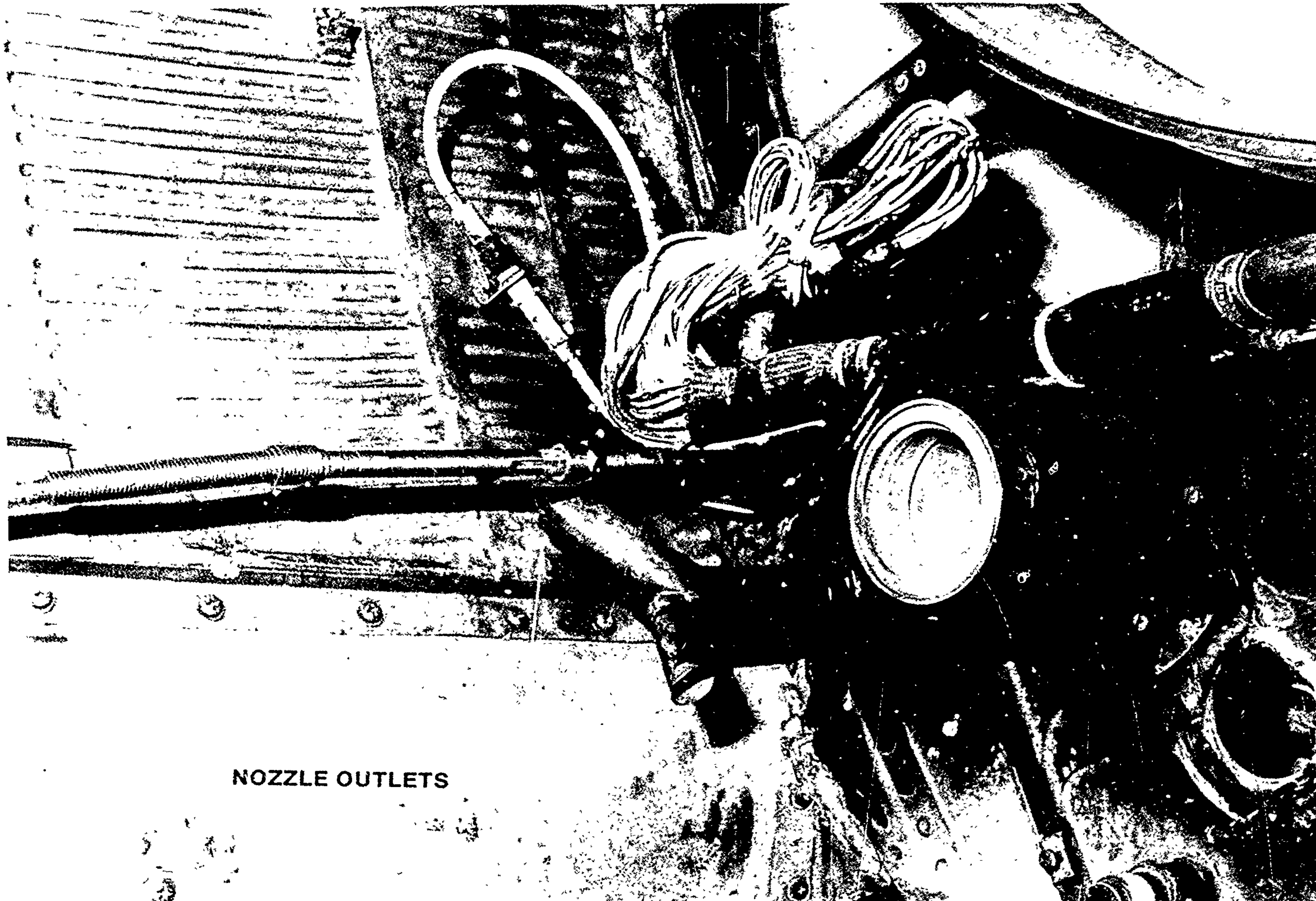


FIGURE 27. F-111 AGENT DISCHARGE NOZZLE

the first in that agent vaporization could be affected within the ambient temperature extremes noted. While there should be no significant effect on the Halon 1301 within this temperature range, testing of Halon 1202 with temperatures in the mid-thirties would have adversely affected vaporization rate and consequent agent distribution. For comparative purposes, some pertinent physical properties of Halon 1202 and 1301 are presented in table 7. The physical properties of a third commonly used agent, Halon 1211, are also shown.

7.2 TEST RESULSTS

7.2.1 Test No. 1301-1 (No Test/TF-30 Engine Failure)

This test was aborted due to the failure of the TF-30 engine.

7.2.2 Test No. 1301-2 (Holding)

This test and all subsequent tests were conducted without the TF-30 engine operating. Test No. 1301-2 simulated a Mach 0.36 holding condition at 3000 feet for the F-111 aircraft. Target ventilation rate through the nacelle was 10.05 lbs/sec. See table 8 for more complete test information. The measured ventilation rates were 10.1 and 10.5 lbs/sec for the first and second runs, respectively. The agent containers used for this test were the standard F-111 containers filled with 10.9 lbs of Halon 1301 and pressurized with nitrogen to 600 psig. The recommended minimum limits of 6 percent agent concentration at all probe locations simultaneously for not less than 0.5 second were not met. See figure 28 for the test results. Although all sampled areas received concentrations well above 6 percent, the distribution was such that the maximum concentration that existed simultaneously throughout the nacelle for 0.5 second was 2.7 percent, as indicated by the cross-hatched area on the graph. This suggests that with improved distribution 10.9 lbs of Halon 1301 may be enough agent to meet the acceptance criteria in the holding flight condition. The only factor that prevented the system from being acceptable in this flight condition was the agent rise and fall timing for probes 1 and 6. The system, however, was improved when compared to Halon 1202 test No. F-2 in Part 1 of this report.

7.2.3 Test No. 1301-3 (Holding)

This test also simulated a Mach 0.36 holding flight condition at 3000 feet, and, except for the quantity of agent, the test parameters were the same as in test No. 1301-2. The agent containers used for this test had an internal volume of 630 cubic inches and was filled with 17.8 lbs of Halon 1301 and pressurized to 600 psig with nitrogen.

Figure 29 shows the composite data from the two runs that constituted test No. 1301-3. As shown by the cross-hatched area on the graph, the data indicate that the 630 in^3 container with 17.8 pounds of Halon 1301 provided sufficient agent to meet the recommended minimum criteria. Although the criteria was satisfied, the data also indicate that the distribution within the nacelle was less than optimum. As with test No. 1301-2, the rise time of agent at probe 6 and the agent decay time at probe 1 greatly limited overall system performance.

TABLE 7. COMPARISON OF HALON AGENTS*

Halon Agent	Chemical Formula	Chemical Name	Boiling Point at 1 atm (°F)	Specific Gravity (Water = 1)	Approx. Critical Temp (°F)	Approx. Press. At Critical Temp (psig)	Approx. Press. At 130 °F(psig)
1202	CBr_2F_2	Dibromodifluoromethane	76	2.28	384	585	23
1301	$CBrF_3$	Bromotrifluoromethane	-72	1.57	153	560	435
1211	$CBrClF_2$	Bromochlorodifluoromethane	25	1.83	309	580	75

* Information obtained from Fire Protection Handbook, 13th edition.

TABLE 8. SUMMARY OF TEST CONDITIONS AND RESULTS FOR PART 2

Test No.	Target Vent.[2] Rate (Lb/Sec	Measured Vent.[3] Rate (Lb/Sec)	Qty of Agent (Lbs)	Container[4] Press. (psig)	Approx. Nacelle Temp. (°F)	Simulated Test Wind	Meets[5] Criteria
1301-1[1]	NA*	NA	NA	NA	NA	NA	NA
1301-2	10.05	10.1/10.5	10.9	600/600	50	Holding	No
1301-3	10.05	10.2/9.9	17.8	600/575	49	Holding	Yes
1301-4	10.05	10.5/10.3	29.7	650/600	49	Holding	Yes
1301-5	30.04	30.4/30.3	17.8	600/600	104	S. L. Dash	No
1301-6	30.04	29.8/29.8	29.7	600/600	90	S. L. Dash	No
1301-7	6.12	6.2/6.3	17.8	600/600	42	Cruise	Yes
1301-8	6.12	6.3/6.6	10.9	600/600	43	Cruise	Yes

Notes

1. Test 1301-1 was aborted due to TF-30 failure. Remainder of tests were conducted without TF-30 operating.

2. Nacelle ventilation rates provided by General Dynamics.

3. Each test consisted of two runs. Numbers shown are indicated ventilation rates at instant of agent discharge for first and second run, respectively.

4. Numbers shown are bottle pressures for first and second run, respecitvely.

5. Criteria is 6% agent concentration existing throughout the nacelle for a duration of 0.5 second.

* NA = Not applicable.

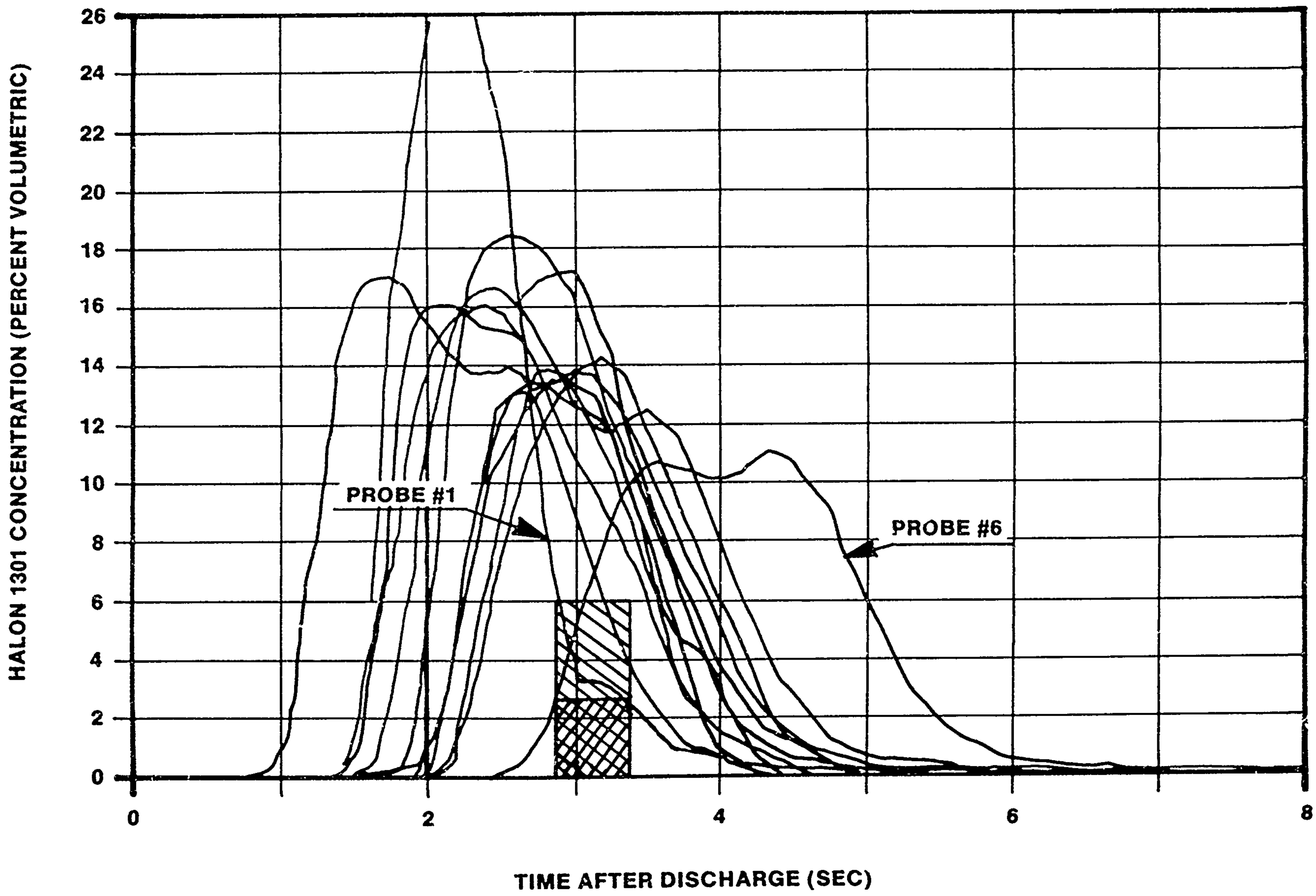


FIGURE 28. AGENT CONCENTRATION FOR TEST NO. 1301-2: HOLDING

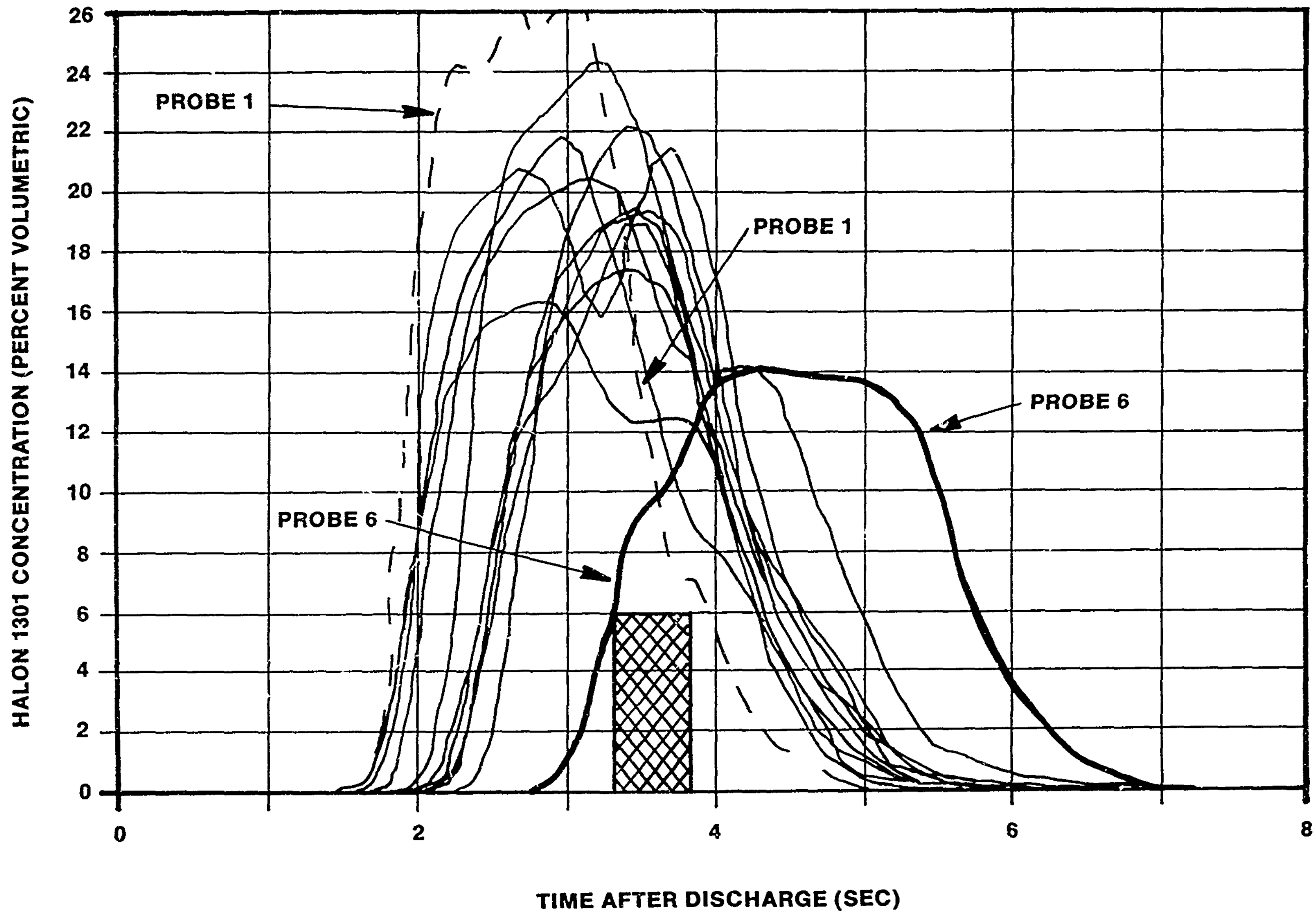


FIGURE 29. AGENT CONCENTRATION FOR TEST NO. 1301-3: HOLDING

7.2.4 Test No. 1301-4 (Holding)

As with the previous two tests, the test simulated a Mach 0.36 holding flight condition at 3000 feet altitude. The quantity of agent, however, was increased to 29.7 pounds of Halon 1301. The agent was discharged from a 1050 in^3 container pressurized with nitrogen to 600 psig at 70°F. See table 8 for a summary of test conditions and results.

Figure 30 shows the recommended minimum criteria was considerably exceeded. The data indicate that approximately 16 percent concentration existed throughout the nacelle for 0.5 second.

7.2.5 Test No. 1301-5 (Sea Level Dash)

This test simulated the F-111 Mach 1.2 sea level dash condition using the 630 in^3 container. Nacelle ventilation rate was approximately 30 lbs/sec, and the quantity of Halon 1301 discharged was 17.8 pounds. See table 8 for additional test information.

Figure 31 shows the composite data for this test. The system did not meet the recommended minimum requirements in the sea-level dash condition. Furthermore, probe 1, which was located at FS 615 in the two o'clock position, indicated no measurable agent concentration. The data indicate that that portion of the nacelle where probe 1 was located is an area that is adversely affected by high ventilation rates. The top and sides of the engine near the firewall (FS 593) are also areas of concern since this is where ventilating air enters the engine bay.

Note in table 8 that the approximate nacelle temperature for this test was 104° F. Elevated nacelle temperatures are the result of compression heating of the ventilating air passing through the fan of the YTF-33 air supply engine. Compression heating will necessarily increase as the YTF-33 is operated at higher power settings. The outside air temperature during this test was approximately 38° F.

7.2.6 Test No. 1301-6 (Sea Level Dash)

This test simulated the F-111 Mach 1.2 sea level dash condition using the 1050 in^3 agent container. Nacelle ventilation rate was approximately 30 lbs/sec, and the quantity of Halon 1301 discharged was 29.7 pounds. See table 8 for additional test information.

Figure 32 shows the composite data for this test. Except for the area sampled by probe 1, the system met the recommended requirements. However, although system performance was improved, overall agent distribution within the nacelle was far from optimum. With regard to probe 1, increasing the quantity of agent by approximately 67 percent over that of the previous test resulted in no significant increase in fire protection in the upper forward portion of the nacelle. This area continues to present a problem with the current distribution system. Keep in mind that the scope of this program did not include sizing the distribution tubing for the size of agent container, nor did it include any alteration of the discharge nozzles.

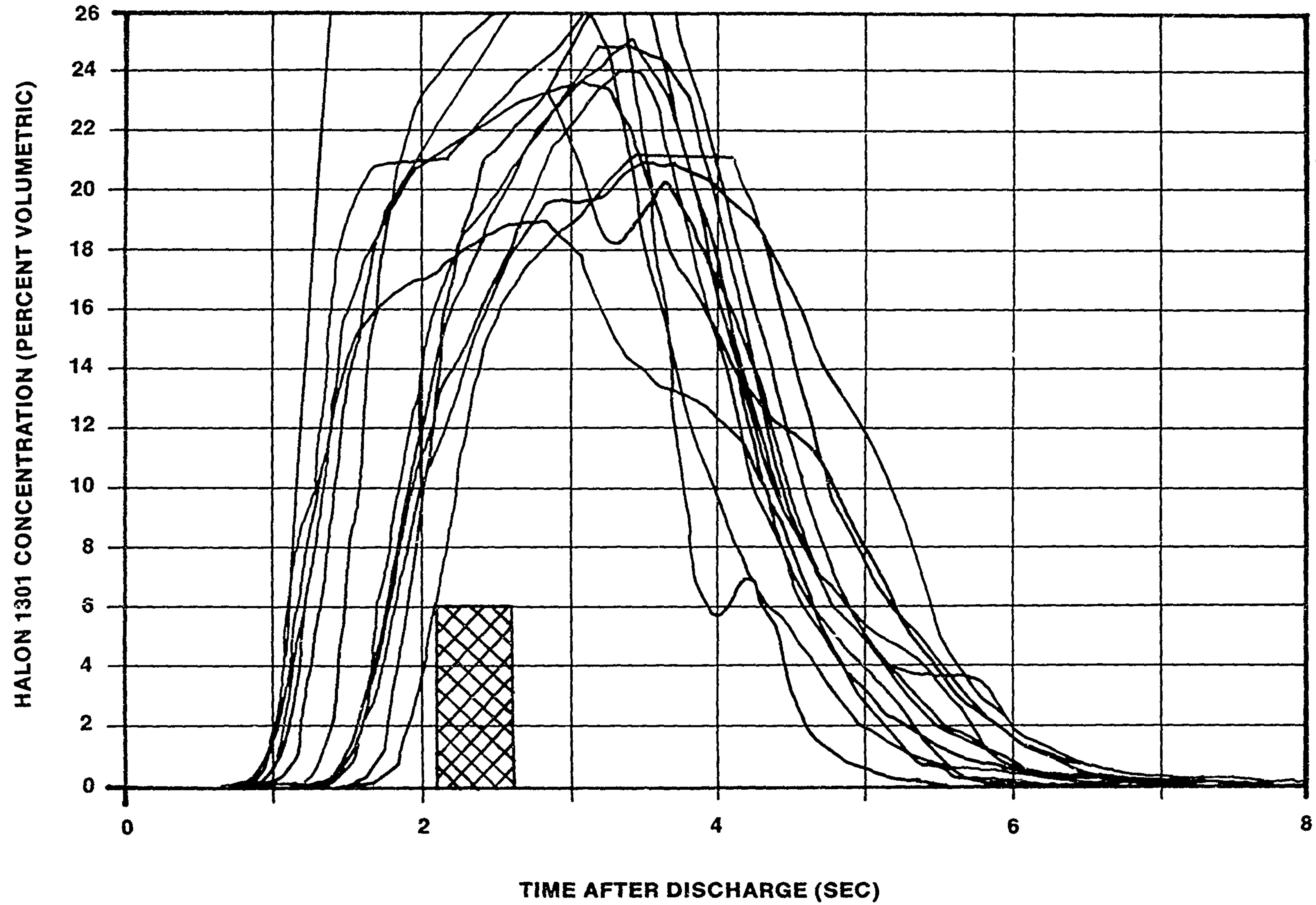


FIGURE 30. AGENT CONCENTRATION FOR TEST NO. 1301-4: HOLDING

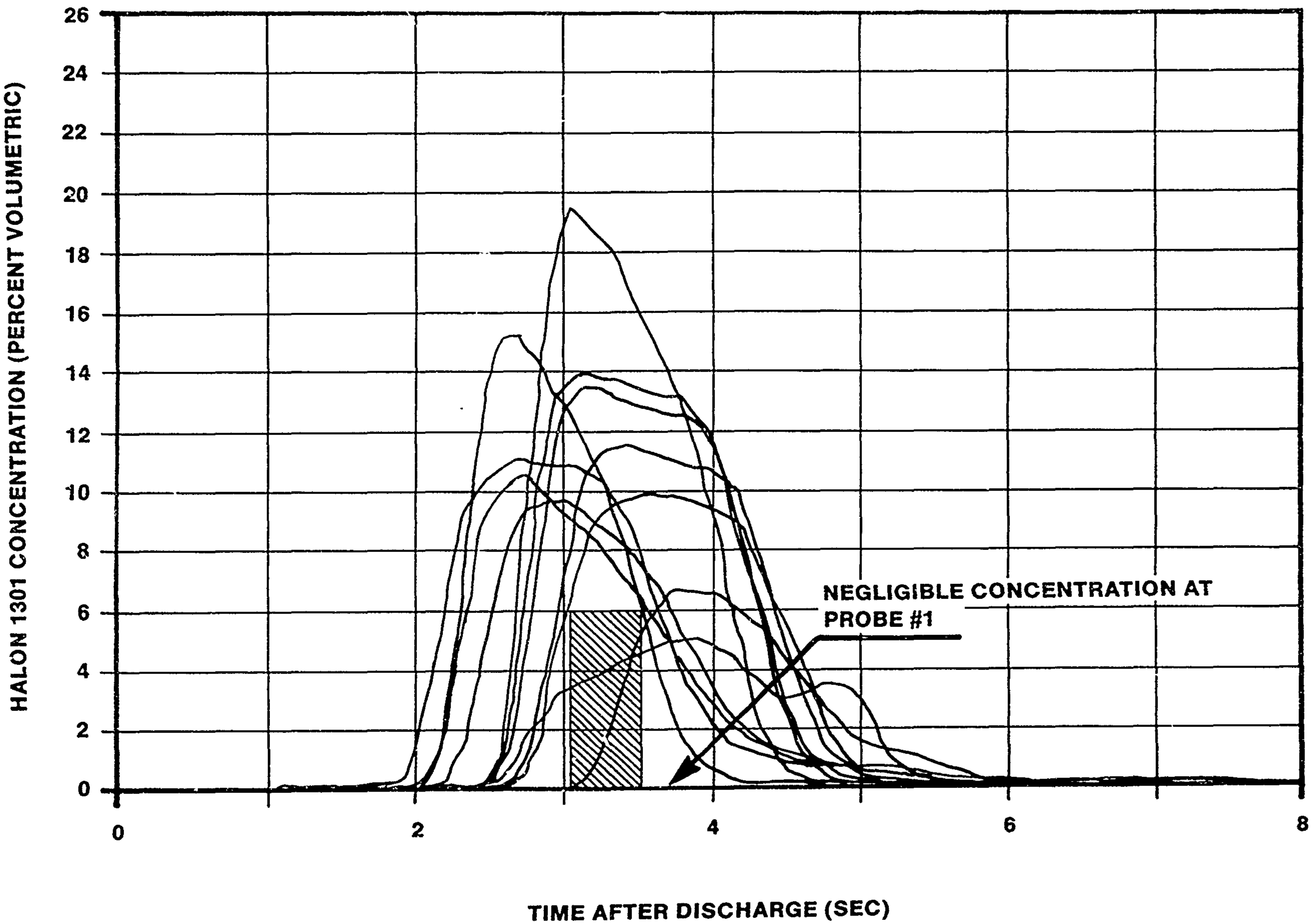


FIGURE 31. AGENT CONCENTRATION FOR TEST NO. 1301-5: SEA LEVEL DASH

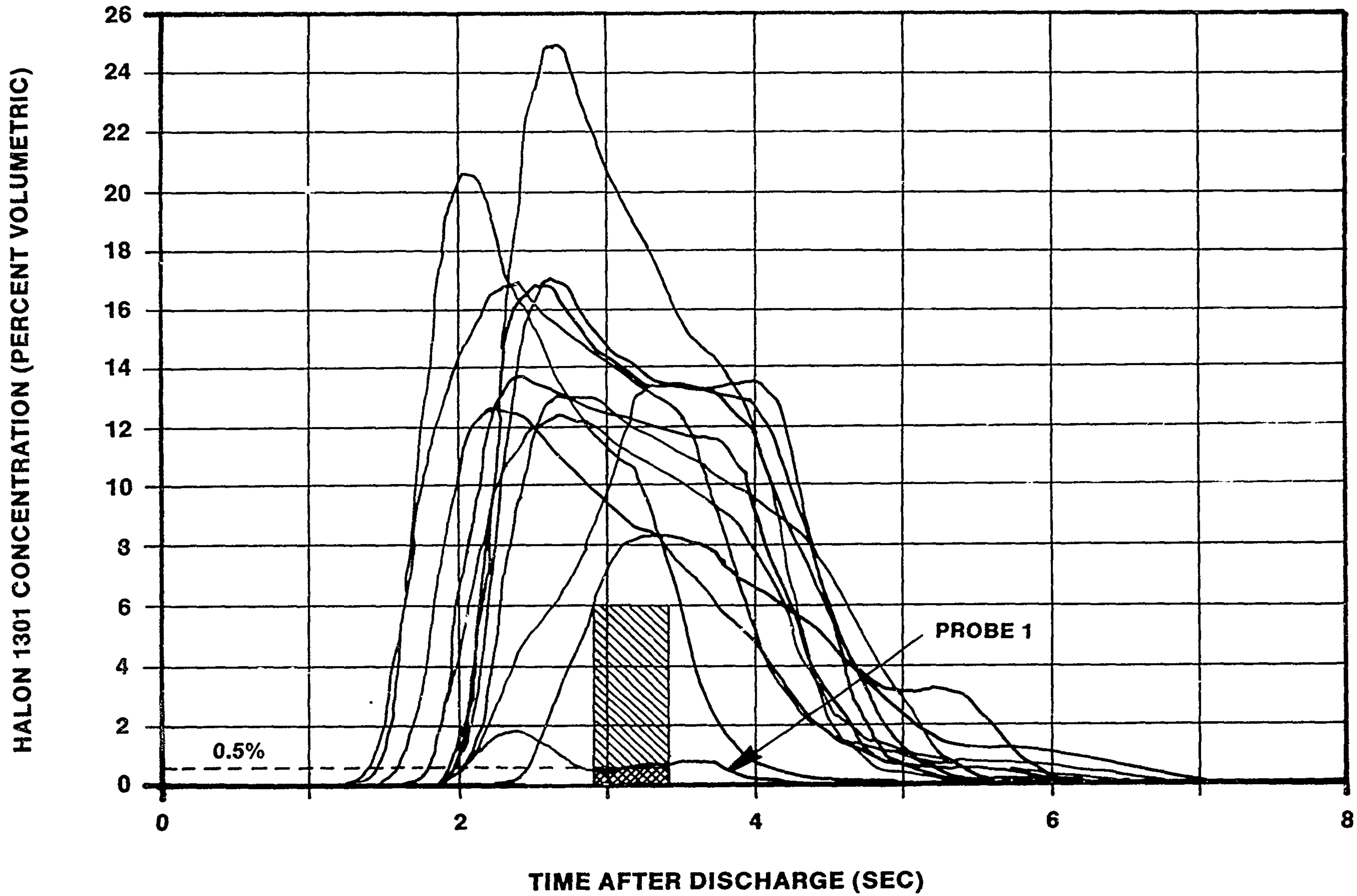


FIGURE 32. AGENT CONCENTRATION FOR TEST NO. 1301-6: SEA LEVEL DASH

7.2.7 Test No. 1301-7 (Cruise)

This test simulated the Mach 0.75 cruise flight condition at 35000 feet using the 630 in^3 containter filled with 17.8 pounds of Halon 1301. The nacelle ventilation rate was approximately 6 pounds per second.

Figure 33 represents the agent distribution as indicated by the 12 sampling probes. The data indicate that the recommended minimum requirements were not only met, but were greatly exceeded. Figures 29, 31, and 33 can be compared to illustrate the significant effect of nacelle ventilating airflow on agent distribution. The 630-cubic inch agent containers filled with 17.8 pounds of agent were used for all three tests, but the nacelle airflow was different for each. For comparison, in order of increasing airflow, figure 33 was at 6 lbs/sec, figure 29 was at 10 lbs/sec, and figure 31 was at 30 lbs/sec.

7.2.8 Test No. 1301-8 (Cruise)

This test simulated the Mach 0.75 flight condition at 35000 feet using the aircraft's standard 385-cubic inch Halon 1202 containers. The containers were filled with 10.9 pounds of Halon 1301 which equates to a 50-percent fill ratio. The nacelle ventilation rate was approximately 6 pounds per second.

Figure 34 shows the agent distribution as indicated by the 12 sampling probes. The data indicate that the recommended minimum requirements for an acceptable system were met in this flight condition. Compare the results of this test with the results of the holding condition test shown in figure 28. The only difference in these two tests was again the ventilation rate. An increase in ventilation rate from 6 lbs/sec to 10 lbs/sec caused the system to to go from acceptable to unacceptable. The configuration of the individual curves changed markedly between tests. Specifically note probes 1 and 6, which are identified on these two figures. In figure 28, the concentration levels indicated by probe 6 not only showed a decrease in concentration when compared to figure 34, but also shifted to the right relative to the other curves. At probe 1, agent dilution occurred more rapidly. The combination of effects shown by these curves caused the system to become unacceptable at the 10 lb/sec nacelle airflow condition. The same change in the concentration curves for probes 1 and 6 can also be noted on figure 29, which illustrates a 10 lb/sec nacelle airflow test with 17.8 pounds of Halon 1301.

7.3 COMPARISON OF HALON 1301 AND 1202 IN THE F-111 AIRCRAFT

Due to the individual objectives of the Halon 1301 and 1202 test programs, only a limited amount of data is available for direct comparison of the extinguishants' performance in the F-111 system. Table 9 summarizes the significant features of the two test programs. Since only the F-111 standard 385-cubic inch agent container was used during the Halon 1202 tests, direct agent comparison is limited to this one container size. Furthermore, for the 385-cubic inch container, only the simulated cruise and holding conditions were common to both programs. Also note that for a recommended container fill ratio of 50 percent, a 385-cubic inch container would hold 15.9 pounds of Halon 1202 or 10.9 pounds of Halon 1301. For the testing in Part 1, the container was only filled with 12.65 pounds of Halon 1202, which is the standard Air Force fill weight for the F/EF-111.

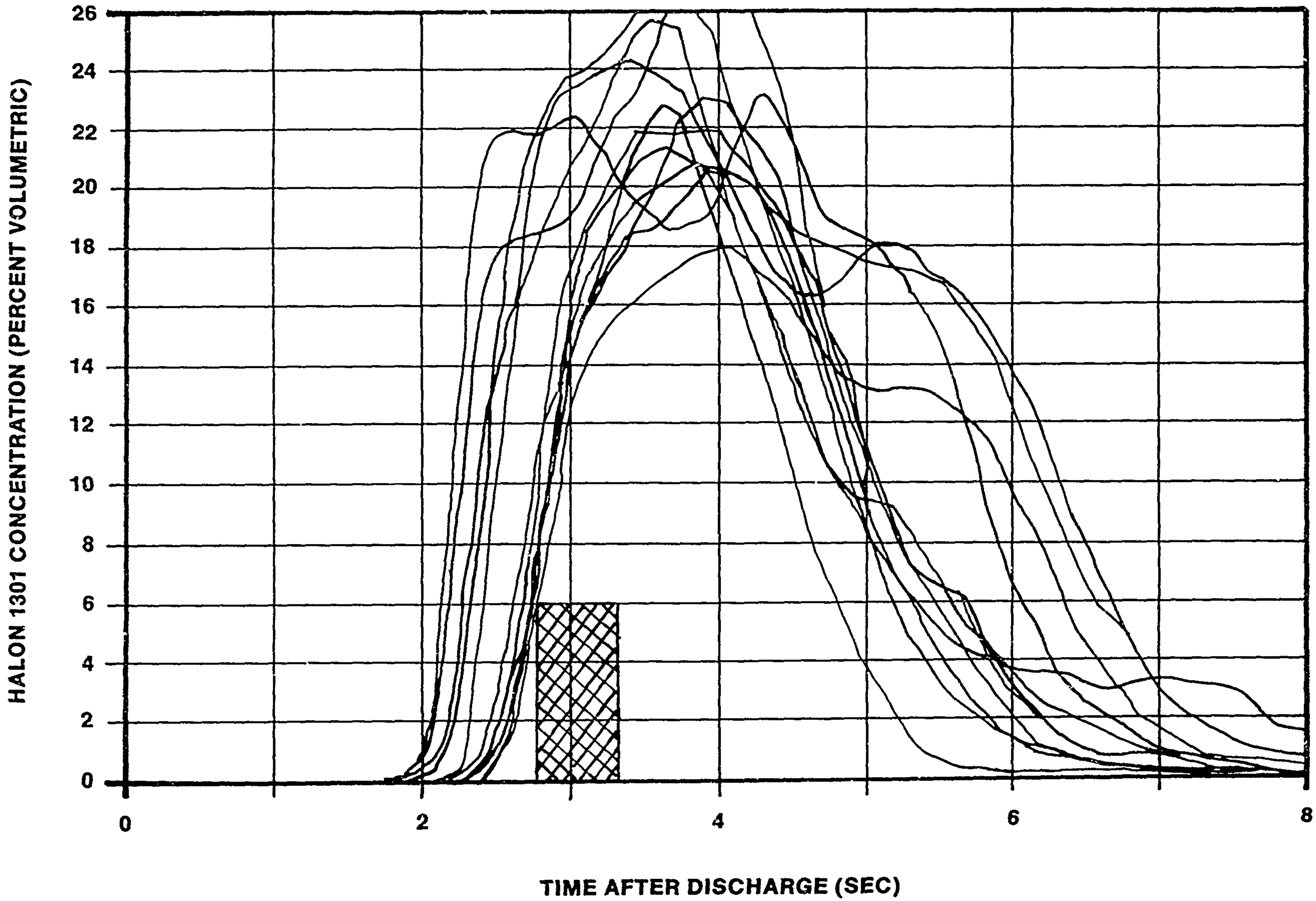


FIGURE 33. ...ENT CONCENTRATION FOR TEST NO. 1301-7: CRUISE

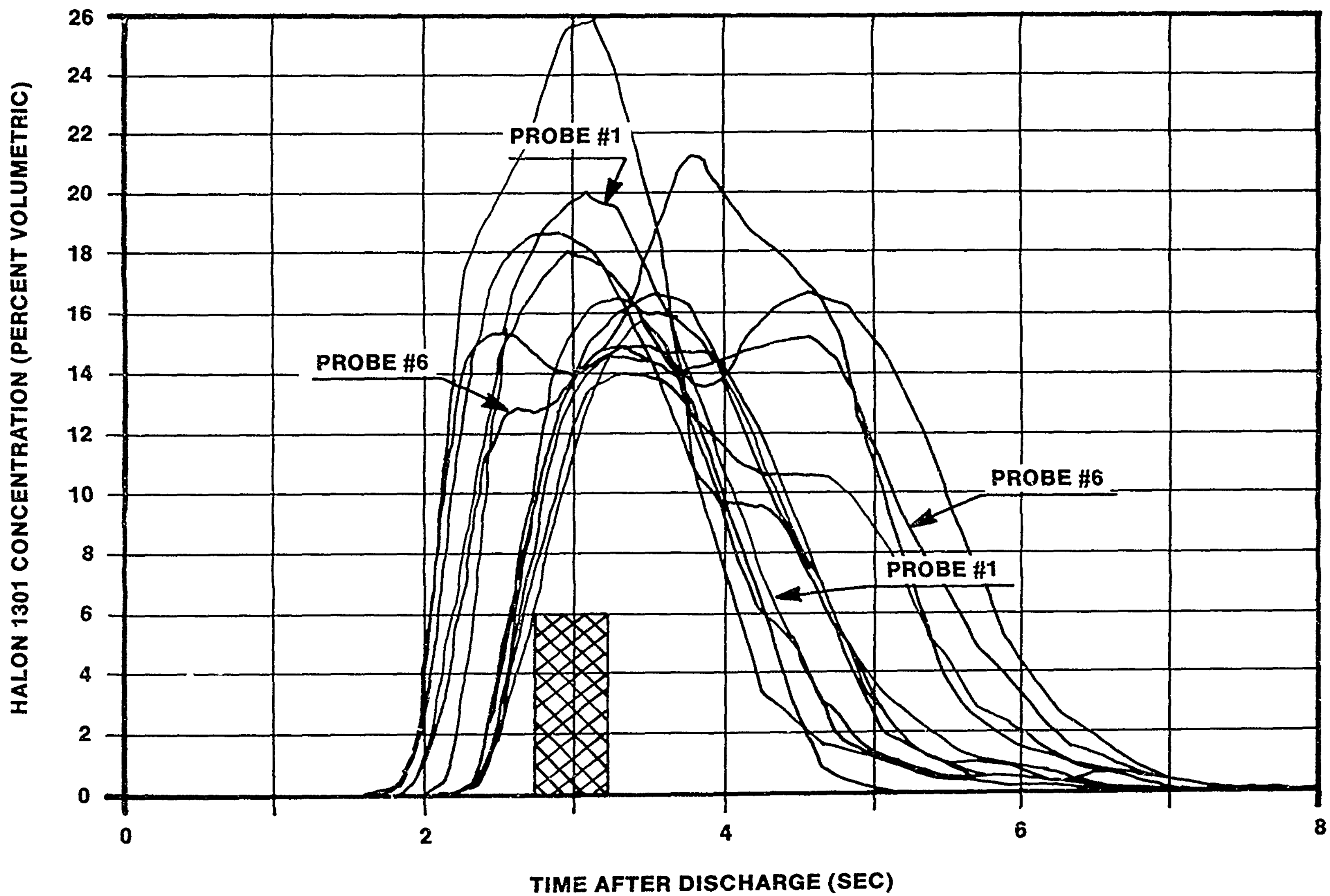


FIGURE 34. AGENT CONCENTRATION FOR TEST NO. 1301-8: CRUISE

TABLE 9. COMPARISON OF HALON 1301 AND 1202 TEST RESULTS

Simulated Test Cond.	Nacelle[2] Nom. Vent Rate (LB/Sec)	Halon 1202 Container Size (IN^3) 385 Pass/Fail	Halon 1202 385 Max. Overall[3] Agt. Conc (%)	Halon 1301[1] Container Size (IN^3) 385 Pass/Fail	Halon 1301 385 Max. Overall[3] Agt. Conc (%)	Halon 1301 630 Pass/Fail	Halon 1301 630 Max. Overall[3] Agt. Conc (%)	Halon 1301 1050 Pass/Fail	Halon 1301 1050 Max. Overall[3] Agt. Conc (%)
Static Gnd Run	4	Pass	>6	NA	NA	NA	NA	NA	NA
Cruise	6	Fail	2						
Holding	10	Fail	<1	Pass	>6	Pass	>6	NA	NA
M .06 @ S.L.	7	Fail	<1	Fail	<3	Pass	>6	Pass	>6
Takeoff	7.5	Fail	<2	NA	NA	NA	NA	NA	NA
S.L. Dash	22/30	Fail	0	NA	NA	NA	NA	NA	NA
				NA	Na	Fail	0	Fail	<1

Notes

1. NA - not applicable. No test was conducted when NA entered in table.

2. Actual ventilation rates varied above and below the figures shown which are approximate target ventilation rates for the F and EF-111 aircraft. For S.L. Dash conditions the 22 and 30 are the EF and F-111 respectively.

3. The maximum overall agent concentration is the maximum percentage that existed throughout the nacelle at all probes simultaneously for 0.5 second.

At the simulated cruise condition with 6 pounds per second of nacelle ventilating air, the 10.9 pounds of Halon 1301 greatly exceeded the system acceptance criteria, while 12.65 pounds of Halon 1202 did not meet the criteria. Also, when discharged through the existing system at this test condition, the distribution of Halon 1301 was much more uniform than the Halon 1202 distribution. This uniformity of Halon 1301 distribution at the 12-sampled locations increases confidence that the same uniformity and acceptable agent concentration will exist throughout the nacelle at all flows up to 6 pounds per second when using 10.9 pounds of Halon 1301.

For the simulated holding test condition with 10 pounds per second nacelle ventilating airflow, neither agent met the acceptance criteria using the 385 cubic-inch container. In general, the Halon 1301 again showed a more uniform distribution. The two areas sampled by probes 1 and 6, however, began to deviate from this uniform distribution pattern at this airflow. This deviation can be seen in figures 15 and 28. These areas were, in fact, the reason the system did not meet the criteria with 10.9 pounds of Halon 1301 at the holding condition. Increasing the quantity of Halon 1301 to 17.8 pounds did extend criteria compliance to include the holding test condition. Although meeting the criteria with 17.8 pounds of Halon 1301, the system's overall performance and uniformity of distribution were sharply reduced by agent distribution at the two areas noted in the 10.9 pound Halon 1301 holding condition test.

While no direct comparison can be made between Halons 1301 and 1202 in the sea level dash condition with 30 pounds per second nacelle ventilating airflow, it can be stated that none of the tests conducted with either agent satisfied the recommended minimum requirements for an acceptable system. These tests included discharges of 12.65 pounds of Halon 1202 and 17.8 pounds and 29.7 pounds of Halon 1301. With the current discharge nozzle system, the sampled area of the nacelle most affected by high ventilation rates was the upper forward portion near the firewall. To a lesser degree, some lower aft portions of the nacelle were also adversely affected. The adverse effect in the upper forward portion of the nacelle is illustrated in figure 35. Figure 35 shows the effect of ventilation rate on Halon 1301 concentration in the area sampled by probe 1. Probe 1 was located in the upper forward nacelle area in the 2 o'clock position at FS 615. The curves on this figure were extracted from the data for tests 1301-7, -3, and -5. Respectively, these tests were simlulated cruise, holding, and sea level dash, and the corresponding airflows were 6, 10, and 30 pounds per second. The amount of Halon 1301 discharged for each of the three tests was 17.8 pounds. At the cruise and holding conditions, agent concentration was well in excess of 15 percent, although the dwell time at the higher ventilation rate was, as expected, of a shorter duration. However, at the sea level dash condition only a trace amount of agent was indicated. For illustrative purposes, the figure indicates that for the cruise condition, a 15 percent concentration was maintained for approximately 2 1/2 seconds. For the holding condition, a 15 percent concentration was maintained for approximately 1 1/2 seconds. However, at the sea level dash condition, the concentration curve lies virtually along the abscissa. There was a significant decrease in agent concentration between holding and sea level dash conditions. The scope of testing was not broad enough to ascertain what nacelle ventilation rate between 10 and 30 pounds per second would cause agent concentration to drop below 6 percent.

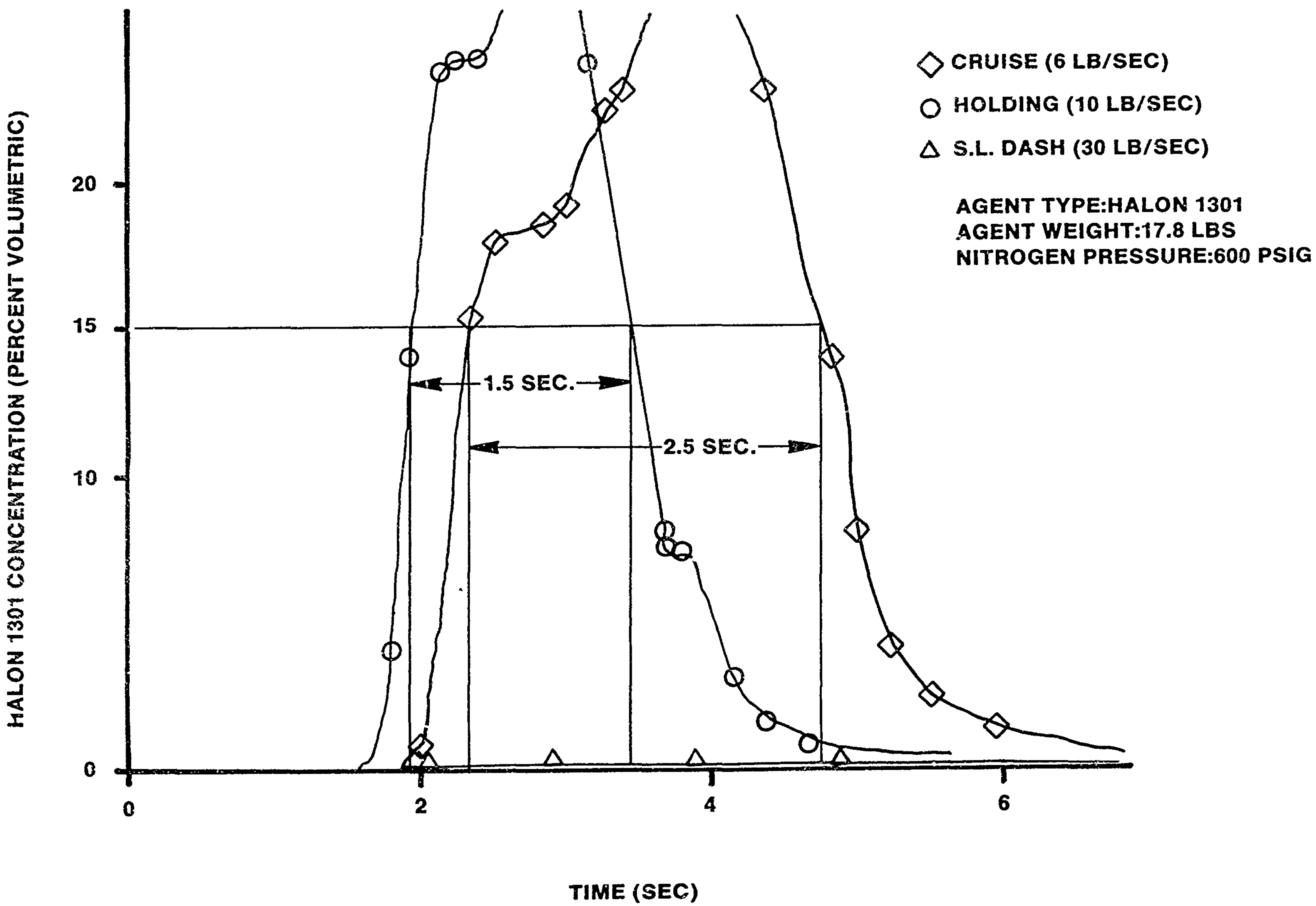


FIGURE 35. EFFECT OF VENTILATION AT PROBE NO. 1

Table 10 shows a pass/fail composite for all Halon 1202 and 1301 tests conducted in Part 1 and Part 2 of this program. Because of limitations previously discussed, all the tests that were planned were not conducted. The selective testing indicated in this table, however, did allow logical conclusions to be reached concerning the overall performance of the existing F/EF-111 agent distribution system. For example, no tests were conducted in the landing approach condition, since the nacelle ventilation rate at that condition falls between the ventilation rates for the cruise and holding conditions.

A note of caution: Although it might appear that a simple, direct, least cost, and logistically attractive method of immediately improving the aircraft's nacelle fire protection would be to substitute 10.9 pounds of Halon 1301 for the 12.65 pounds of Halon 1202 in the existing, on-board 385-cubic-inch agent container, such an approach would be dangerous. Original system design information indicated that the agent container is mounted in an area that can reach an environmental temperature of 275° F, due in part to aerodynamic heating. Also, Walter Kidde Company, the system supplier, indicates that the current Halon 1202 container was designed for an environmental temperature of 275° F. Their information further indicates that when charged with 12.65 pounds of Halon 1202 and initially pressurized with nitrogen to 600 psig at 70° F, the internal container pressure at 275° F would be 1100 psig. The container charged with 10.9 pounds of Halon 1301 and initially pressurized with nitrogen to 600 psig would have an internal pressure of approximately 2100 psig at 275° F, which would exceed the safe design limits of the container. Using 1100 psig as the safe upper pressure limit, the upper temperature limit to maintain container pressure below 1100 psig would be approximately 160° F, which is above the critical temperature (152.6° F) of Halon 1301.

7.4 FUTURE TEST CONSIDERATIONS

Tests conducted with Halon 1202 in Part 1 disclosed that the current F-111 nacelle fire extinguishing system failed to meet the recommended minimum requirements for acceptance in any condition tested except the aircraft parked/engine operating condition. However, examination of individual and composite sampling probe data indicates that an improved Halon 1202 system is possible. In most tests, agent concentration peaks and dwell-time were of sufficient magnitude to individually meet criteria, but in the composite picture, distribution was inefficient. In other cases of areas deficient in concentration, agent was simply not being directed correctly. Many areas received concentrations far in excess of that required for fire extinguishment. The great variation in the concentrations recorded at the individual probe locations suggest that the problem may not be with the type or quantity of agent but with the distribution system. A more comprehensive test program directed toward improvement in uniformity of distribution could result in the development of an acceptable system using Halon 1202. This comprehensive program should include variations in agent quantity, agent discharge rate, modifications of the distribution nozzle system, and additional ventilation rates to fill in data gaps that existed in the current program. One essentially untested factor that will be difficult to address, however, is the effect of extremely low environmental temperatures on the performance of Halon 1202. With a boiling point of 76° F at standard sea level atmospheric pressure, some portion of the agent may linger or remain in liquid form. This, in fact, was visually evidenced in testing conducted in Part 1. Cold soaking of the agent container at various temperature levels to -60° F could partially address this question. Of further interest is

TABLE 10. SUMMARY OF F/EF111 NACELLE EXTINGUISHING SYSTEM TEST RESULTS

AGENT / QUANTITY LBS	AIRCRAFT PARKED ENGINE OFF	AIRCRAFT PARKED EJECTOR PUMPING	CRUISE	LANDING APPROACH	TAKE OFF	HOLDING	SEA LEVEL DASH F-111	SEA LEVEL DASH EF-111
1202 / 12.65	FAIL	PASS	FAIL		FAIL	FAIL	FAIL	FAIL
1301 / 10.9			PASS			FAIL		
1301 / 17.8			PASS			PASS	FAIL	
1301 / 29.7						PASS	FAIL	

the fact that with a standard 50 percent fill ratio, the F-111's current 385-cubic-inch agent container can be filled with 15.9 pounds of Halon 1202, thus allowing an immediate 25 percent increase in available agent.

The use of Halon 1301 could reduce the low temperature operational considerations significantly, due to its -72° F boiling point at standard atmospheric pressure. Furthermore, the current on-board system tests conducted with this agent show that F-111 nacelle fire protection is extended beyond the aircraft parked/engine operating condition into the aircraft's operational flight envelope, even with 10.9 pounds of Halon 1301. Converting the F-111 system to Halon 1301 should entail the same comprehensive testing approach as described for Halon 1202, including container cold soaking tests and distribution system modifications to further improve uniformity of distribution. Also, container relocation must be considered, since the critical temperature of Halon 1301 is 152.6° F. The current container is mounted in a compartment where temperatures can rise much above this point. Above the critical temperature, the liquid phase ceases to exist, the agent behaves as a gas, but can no longer be liquified at any pressure. Container relocation would also require additional testing to determine the effect of longer distribution lines on agent discharge.

Future testing should not be limited to only the normal cruise flight condition specified by MIL-E-22285. Test experience with this program clearly showed that the cruise condition does not provide the most severe test environment for the engine compartment fire extinguishing system in the F/EF-111 aircraft.

A final consideration for future testing would be a determination of the effect that removal of the originally installed firewall flapper doors had on extinguishing system performance

VIII CONCLUSIONS

Based upon the results of this test program, it is concluded that:

1. Halon 1301 is a viable replacement for Halon 1202 in the F/EF-111 nacelle extinguishing system.

2. Using 10.9 pounds of Halon 1301, the current F-111 nacelle extinguishing agent distribution system will provide adequate fire protection for nacelle ventilation rates up to 6 pounds per second.

3. Using 17.8 pounds of Halon 1301, the current F-111 nacelle extinguishing agent distribution system will provide adequate fire protection for nacelle ventilation rates up to 10 pounds per second.

4. Increasing the weight of agent discharged through the current F-111 extinguishing agent distribution system from 17.8 pounds to 29.7 pounds will extend nacelle fire protection beyond a ventilation rate of 10 pounds per second, but still will not provide adequate protection at a ventilation rate of 30 pounds per second in the sea level dash condition.

5. With the current agent distribution system, the portion of the nacelle most adversely affected by high ventilation rates is the forward area between FS 593 and FS 625.

6. The existing, on-board Halon 1202 agent contai er should not be utilized with Halon 1301 due to the high vapor pressure of Halon 1301 and the strength of the container.

7. Environmental temperatures will preclude the storage of a Halon 1301 container in the compartment in which the current Halon 1202 container is mounted.

8. The existing agent distribution system, including discharge nozzles, can be modified to improve nacelle fire protection while minimizing agent weight.

9. MIL-E-22285 does not adequately define the installation and testing parameters necessary to insure an effective nacelle fire extinguishing system.

IX RECOMMENDATIONS

1. A thorough feasibility study should be undertaken to determine the practicality of substituting Halon 1301 for Halon 1202 in the F/EF-111 nacelle extinguishing system.

2. If Halon 1301 is selected as the agent-of-choice, the existing distribution system should be redesigned and optimized specifically for use with 1301.

3. Any redesign and optimization should be accomplished under full-scale conditions which are fully representative of the entire operational envelope of the F/EF-111 aircraft.

4. MIL-E-22285 should be revised to insure that engine compartment extinguishing system acceptance testing is conducted under the flight and/or ground operating conditions that most adversely affect system performance.

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